DEPARTMENT OF DEFENSE

MILITARILY CRITICAL TECHNOLOGIES LIST

SECTION 7: ENERGY SYSTEMS TECHNOLOGY

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Under Secretary of Defense, Acquisition, Technology and Logistics
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PREFACE

A. THE MILITARILY CRITICAL TECHNOLOGIES PROGRAM (MCTP)

The MCTP supports the development and promulgation of the congressionally mandated Militarily Critical Technologies List (MCTL) and the Developing Science and Technologies List (DSTL).

Congress assigns the Secretary of Defense the responsibility of providing a list of militarily critical technologies (the MCTL) and of updating this list on an ongoing basis. The MCTL identifies technologies crucial to weapons development and has been a key element in evaluating U.S. and worldwide technological capabilities. The MCTP has provided the support for a wide range of assessments and judgments, along with technical justifications for devising U.S. and multilateral controls on exports. The DSTL, another MCTP product, identifies technologies that may enhance future military capabilities and provides an assessment of worldwide science and technology (S&T) capabilities.

The MCTP process is a continuous analytical and information-gathering process that refines information and updates existing documents to provide thorough and complete technical information. It covers the worldwide technology spectrum and provides a systematic, ongoing assessment and analysis of technologies and assigns values and parameters to these technologies.

TWGs, which are part of this process, provide a reservoir of technical experts who can assist in time-sensitive and quick-response tasks. TWG chairpersons continuously screen technologies and nominate items to be added or removed from the list of militarily critical technologies. In general, TWG members are drawn from about 1,000 subject matter experts (SMEs) from the military Services, DoD and other federal agencies, industry, and academia. A balance is maintained between public officials and private-sector representatives. TWGs collect a core of intellectual knowledge and reference information on an array of technologies, and these data are used as a resource for projects and other assignments. Working within an informal structure, TWG members strive to produce precise and objective analyses across dissimilar and often disparate areas. Currently, the TWGs are organized to address 20 technology areas:

- Aeronautics
- Armament and Energetic Materials
- Biological
- Biomedical
- Chemical
- Directed and Kinetic Energy Systems
- Electronics
- Energy Systems
- Ground Combat Systems
- Information Security
- Information Systems
- Lasers, Optics, and Imaging
- Processing and Manufacturing
- Marine Systems
- Materials and Processes
- Nuclear Systems
- Positioning, Navigation, and Time
- Signature Control
- Space Systems
- Weapons Systems

B. THE MILITARILY CRITICAL TECHNOLOGIES LIST (MCTL)

The expanded MCTL provides a coordinated description of existing goods and technologies that DoD assesses would permit significant advances in the development, production, and use of military capabilities by potential adversaries. It includes goods and technologies that enable the development, production, and employment of weapons of mass destruction (WMD) and their means of delivery. It includes discreet parameters for systems; equipment; subassemblies; components; and critical materials; unique test, inspection, and production equipment; unique software, development, production, and use know-how; and worldwide technology capability assessments.

C. LEGAL BASIS FOR THE LIST OF MILITARILY CRITICAL TECHNOLOGIES

The Export Administration Act (EAA) of 1979 assigned responsibilities for export controls to protect technologies and weapons systems. It established the requirement for DoD to compile a list of militarily critical technologies. The EAA and its provisions, as amended, were extended by Executive Orders and Presidential directives.

D. USES AND APPLICATIONS

The MCTL is not an export control list. Items in the MCTL may not appear on an export control list, and items on an export control list may not appear in the MCTL. The document is to be used as a reference for evaluating potential technology transfers and for reviewing technical reports and scientific papers for public release. Technical judgment must be used when applying the information. It should be used to determine if the proposed transaction would result in a transfer that would give potential adversaries access to technologies whose specific performance levels are at or above the characteristics identified as militarily critical. It should be used with other information to determine whether a transfer should be approved.

This document, MCTL Section 7, Energy Systems Technology supersedes MCTL Part I, Section 14, Power Systems Technology.

INTRODUCTION

A. ORGANIZATION OF THE MILITARILY CRITICAL TECHNOLOGIES LIST (MCTL)

The MCTL is a documented snapshot in time of the ongoing MCTP militarily critical technology process. It includes text and graphic displays of technical data on individual technology data sheets.

Each section contains subsections devoted to specific technology areas. The section front matter contains the following:

- *Scope* identifies the technology groups covered in the section. Each group is covered in a separate subsection.
- *Highlights* identify the key facts in the section.
- *Overview* discusses the technology groups identified under "Scope."
- *Background* provides additional information.

Each technology group identified under Scope has a subsection that contains the following:

- *Highlights* identify the key facts found in the subsection.
- *Overview* identifies and discusses technologies listed in data sheets that follow.
- *Background* provides additional information.
- *Technology Data Sheets,* which are the heart of the MCTL, present data on individual militarily critical technologies.

B. TECHNOLOGY DATA SHEETS

The technology data sheets are of primary interest to all users. They contain the detailed parametric information that managers, R&D personnel, program managers (PMs), and operators need to execute their responsibilities.

- *Critical Technology Parameter(s)* includes the parameter, data argument, value, and level of the technology where its technical performance would permit significant advances in the development, production, and use of the military capabilities of potential adversaries.
- *Critical Materials* are those materials that are unique or enable the capability or function of the technology.
- *Unique Test, Production and Inspection Equipment* includes that type of equipment that is critical or unique.
- *Unique Software* is software needed to produce, operate, or maintain this technology that is unique.
- *Major Commercial Applications* addresses commercial uses of this technology.
- *Affordability Issues* are those factors that make this technology an affordability issue.
- *Export Control References* indicate international and U.S. control lists where this technology is controlled.

Note: Export control references are:

WA ML 2	(Wassenaar Arrangement Munitions List Item)
WA Cat 1C	(Wassenaar Dual Use List Subcategory)
MTCR 17	(Missile Technology Control Regime Item)
NTL B3	(Nuclear Trigger List Subitem – Nuclear Suppliers Group)

NDUL 1	(Nuclear Dual Use List Item – Nuclear Suppliers Group)
AG List	(Australia Group List)
BWC	(Biological Weapons Convention)
CWC	(Chemical Weapons Convention)
USML XII	(United States Munitions List Category – ITAR)
CCL Cat 2B	(Commerce Control List Subcategory – EAR)
NRC A	(Nuclear Regulatory Commission Item)

Background provides a description of the technology.

SECTION 7—ENERGY SYSTEMS TECHNOLOGY

Scope

Highlights

- Energy systems are difficult to define because they range from milliwatts to many terawatts and from millivolts to megavolts. Each range of the systems contains unique requirements.
- Energy system technologies provide for power generation and energy conversion, energy storage, and power conditioning.
- The military's goal is to increase system power densities by two to five times, depending upon the specific system.
- Power converters typically take up approximately 30 to 40 percent of system volume.
- Stringent military requirements demand reliable, intelligent/survivable, and affordable energy systems that can perform in battlefield threat environments and in ground support equipment.
- The military's need for reduced volume and weight, increased performance, and graceful degradation makes military and commercial compatibility difficult to accommodate in many applications.
- Special power system needs for the military include increased operational temperature range (–50 to 150 °C), reduced size and weight of the platform or device, increased radiation hardening, safety, and improved reliability, survivability, and maintainability.
- Advances in power electronics, systems integration, integrated packaging, and thermal management will drive the performance advances and affordability in the state of the art.

OVERVIEW

This section of the Militarily Critical Technologies List (MCTL) addresses energy systems, specifically the generation, storage, and conditioning required to deliver electrical power from the initial source (also referred to as a prime power source) to military systems load requirements.

Figure 7.0-1 illustrates the Energy Systems taxonomy and how this section of the MCTL is organized. The technology area is divided into four subsections: Integrated Electrical Power and Energy Systems (7.1), Energy Conversion and Power Generation (7.2), Energy Storage (7.3), and Power Conditioning, Control, and Distribution (7.4).

Section 7.1 addresses technologies for the integration of complete systems for all types of military platforms—except space systems, which are addressed in Section 19 of the MCTL. Pulsed power and inverter subsystems are also covered in Section 7.1. Section 7.1 also addresses certain pervasive technologies that are required at all levels of integration—from components through completely integrated systems. These include materials, packaging, interconnections, thermal management, and electromagnetic compatibility (EMC).

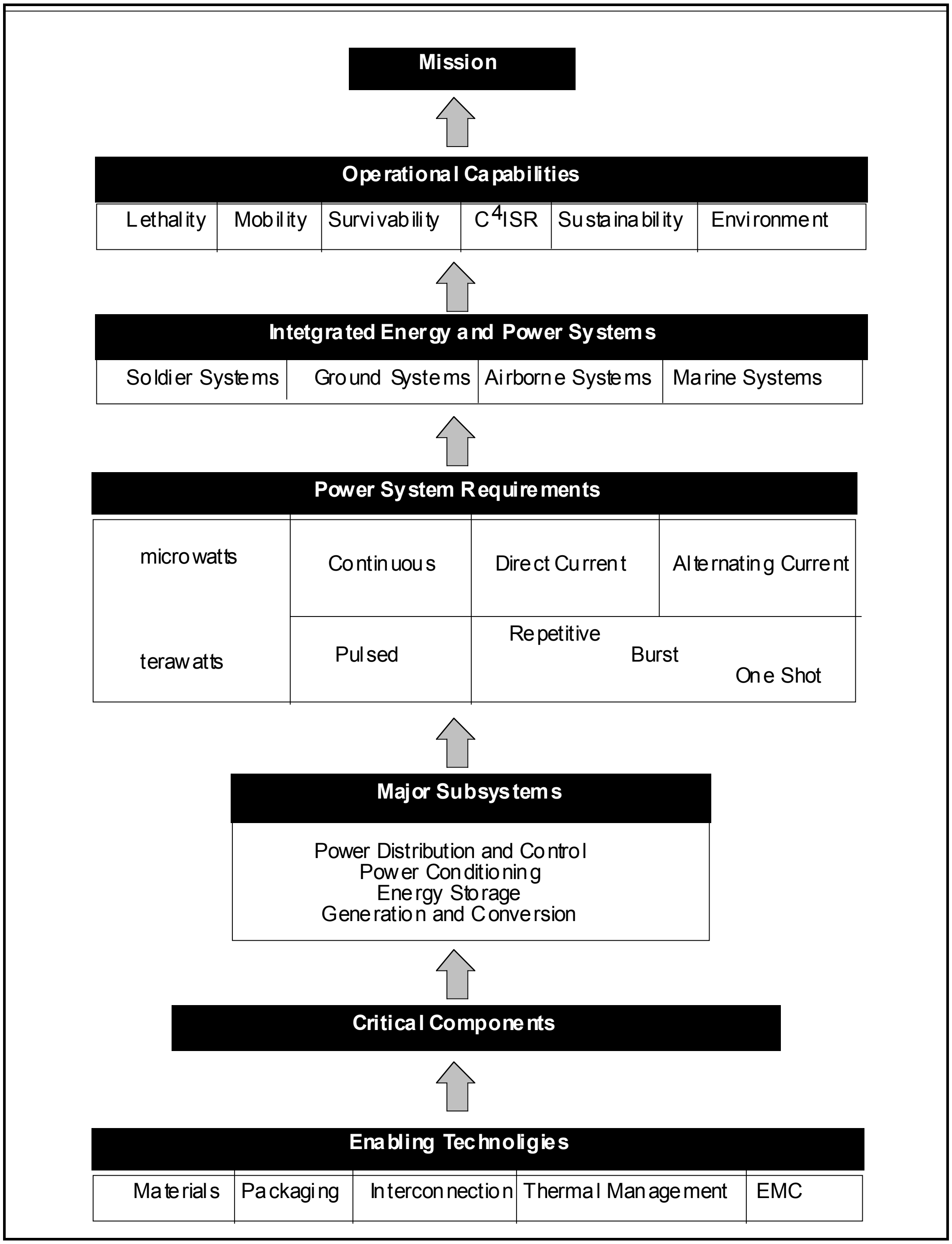

Figure 7.0-1. Energy Systems Taxonomy

Power systems requirements are driven by load requirements, which range from demand for continuous power to extremely high peak power for one-shot applications. Tailoring the power to a given load generally requires the integration of several stages, including power generation from some primary source, energy conversion for energy storage and extraction of energy in useable form from storage, and electrical power conditioning, control, and distribution.

BACKGROUND

To create useful power, energy is converted from potential energy to kinetic energy and either stored or conditioned and then delivered to a load. This power can be provided continuously or in pulses. Varying military applications require power to be delivered in time periods ranging from extremely short durations (on the order of nanoseconds, 10^{-9} sec) to continuous duty. Specifically, many specialized advanced weapons require pulsed power. Power electronics and other components used in continuous systems have characteristics different from those used in pulsed systems.

Not only are the materials and component advancements in energy systems key, but design philosophies are also essential for delivering a product in the most efficient and affordable manner. The approach of Synchronizing Enabling Technologies (SETs) is the assessment and the development or implementation of enabling technologies to support a thrust area. It is analogous to knowing the ingredients for a recipe and timing their preparation and introduction into the amalgam. To be successful, a proper assessment of needed enablers should be completed during the early phases of a technology's development. Enablers can range from parallel developments to components or materials, such as composites, in the research and testing phase. Synchronizing technologies is an important management issue that will be discussed further in relevant technology areas.

Military power and energy systems requirements are different from civil products in several ways. Size and weight are more severely constrained, particularly in the context of complete integrated systems. Military systems are also required to be highly reliable and survivable in extremely hostile environments, comprising both weapons effects and extremes of temperature, shock, and vibration. Because of the military's stringent performance requirements, the advances in power electronics packaging and integration and in thermal management will be the key drivers in the successful realization of the military's future vision.

The past decade has been characterized by a rapidly growing demand for electrical power in the consumer market. The range of products includes long-life, low power sources for embedded medical applications; high-energy-density storage capable of delivering 10s to 100s of watts to power portable electronic devices; and high power systems [100s of kilowatts for hybrid electric vehicle (EV) drives and megawatts for remote and distributed electrical power]. While much of the enabling design and manufacturing technology will be derived from commercial-off-the-shelf (COTS) advances, extensive testing and tailoring will be required to adapt the products and technologies for use in military environments.

In addition, in some areas, the power requirements will remain predominately military in nature. These include extremely high pulse power for directed energy weapons (DEWs), active protection, electric armaments, and platform propulsion. For example, the Joint Chiefs of Staff (JCS) have recognized high-density power converter systems as a technology priority, and these systems will require new technology design and packaging approaches that will revolutionize the entire power electronics industry.

SECTION 7.1—INTEGRATED ENERGY AND POWER SYSTEMS

Highlights

- Electrical/electronics military systems designers must include power system architecture early in their system designs to maximize overall system performance.
- Integrated functionality and electronic packaging are keys to future design.
- Thermal management, power distribution, and connectivity considerations will drive future systems design and input/output (I/O) counts because of the increase in packaging density and the increased reliability needs.

OVERVIEW

Electrical power systems are intrinsic elements of offensive and defensive operation in the modern military. However, energy/power systems cannot be considered as separate entities because they are always part of a larger system. Examples of these systems include communications, weapons detection, computation, weapons, protective systems, weapons guidance, and sensors. As illustrated in Figure 7.1-1, power systems requirements range from microwatts to terawatt peak powers. In many cases, a single platform will comprise systems requiring a variety of voltage, current, and power levels. This will demand the synergistic functional integration of several different technologies to accommodate the wide-ranging requirements.

This section addresses

- Integrated platform/system level technologies, which include systems for ground, marine, and air combatants support platforms and individual soldier systems
- Major military systems, including complex subsystems underlying a significant combat capability, including integrated converters/inverters and pulsed power systems
- Pervasive enabling/supporting technologies, such as thermal management, packaging, materials, EMC, and interconnections.

Advancing technologies are increasing the capabilities of warfighters, including the individual soldier. Current estimates indicate that 25 to 35 percent of the weight carried by the soldier is related to power generation. Because of the high weight burden devoted to power supply, alternative power sources are in development. Although this example portrays the soldier system, it also applies to much larger systems, where weight and volume are important considerations.

Power systems architecture is critical to the design of future systems. In military systems, electric power enables the system operator to do more functions more precisely and with less total energy. Further, the military system designed with an architecture of redundant or transferable power places power sources close to loads and reduces total system vulnerability.

BACKGROUND

Strong multidiscipline systems-level approaches will be critical in the evolution to advanced packaging capabilities. Change is required to overcome the mindset of single-level packaging. Effecting this change will be difficult because of the subsystem mentality that exists and the way parts are designed and manufactured in today's environment.

Improvements in basic materials science and power-generating components, coupled with growing demand for electrical power for a wide range of civil and military applications, are driving rapid advances in critical components and in overall system design.

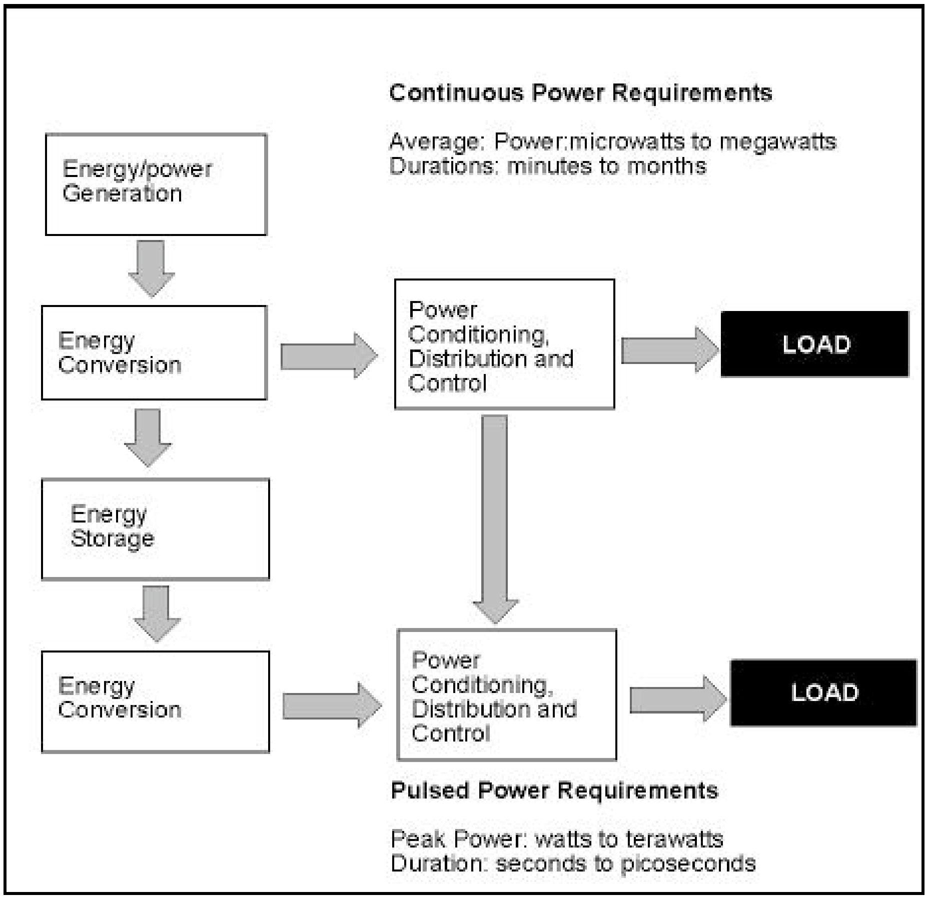

Figure 7.1-1. Integrated Systems—Schematic Overview

LIST OF MCTL TECHNOLOGY DATA SHEETS
7.1. INTEGRATED ENERGY AND POWER SYSTEMS

MCTL DATA SHEET 7.1-1. CONVERTERS AND INVERTERS

Critical Technology Parameter(s)	Specific power > 2 kW/kg Power density > 1.2 kW/L System efficiency > 97% Operating temperature > 150 °C Voltages > 13,000 V Switching frequency @ > 100 kW > 20 kHz
Critical Materials	SiC power semiconductors; WB power semiconductors; microprocessor-based controllers.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Simulation software yielding findings that produce changes to end-state conditioning for functioning inv. GVU placed into military system may require export restriction.
Major Commercial Applications	High power-density, high-temperature, and high-reliability aerospace and satellite power conversion systems; utility power distribution and transmission; power quality devices; Flexible AC Transmission Systems (FACTS); commercial marine propulsion; battery energy-storage systems; power supplies; industrial motor drives (for industries such as paper, steel manufacturing, automotive production); automation equipment; EVs and HEVs; computer power supplies; fuel-cell controllers; high-speed transportation [magnetically levitated trains (Maglevs)].
Affordability Issues	Present requirement is military but could be required on future commercial systems as packaging becomes denser.
Export Control References	USML XI

BACKGROUND

Power Electronics Converters and Inverters

Today, the terms converter and inverter are used interchangeably. The advent of pulse width modulation and IC control chips has changed traditional concepts to new ones, where 2-quadrant and 4-quadrant conversion/inversion are more appropriate issues. A 4-quadrant inverter inverts when it sends volts and hertz to the load and converts during the time when power is flowing from the load to the inverter. In most cases, high-power converters and inverters are physically the same. Only software programming distinguishes the inversion or conversion functions. A notable exception is the age-old diode and silicon-controlled rectifier (SCR) bridges. A power electronic converter changes electric power in one form to electric power in another form—AC to DC, AC to AC, DC to AC, and DC to DC. Converters can change the power generated by a source to a common distribution voltage, and, at the load, converters can change the distribution voltage to the type of power the load needs. Sources can be set to their optimum operating points. Distribution is optimized. Point-of-use conversion ensures that loads get the power they need.

Pulse Width Modulation (PWM)

PWM has been widely used for small- to medium-size converters and more recently up to several hundred MegaVolt-Amp (MVA) applications. In a switch-mode power electronic converter, the switches are ON or OFF. Within a switching cycle, the duration of ON and OFF states is controlled to cause an average value voltage or current to be created from an input signal. Transitions between ON and OFF are minimized to the maximum extent practical. In most cases, the nature of the switch limits ON and OFF transitions. From this simple physical behavior, an array of switches, ON and OFF patterns, and algorithms are possible to create desired signals. The part of the switch cycle during which voltage is transferred and current is conducted is called a pulse. The width of this pulse is said to be modulated by the control signal turning the switch ON and OFF—hence, PWM.

Today's PWM converters can be programmed to supply a range of voltages, currents, frequencies, and power factors over a range of varying input waveforms. They are programmable digital waveform generators. From this perspective, the difference between motor controllers, power supplies, and active filters is minimal. This is one of the power electronic building block (PEBB) principles: hardware based on standard building blocks and software programming to enable specific system functions. In fact, several commercial manufactures supply products based on PEBB principles. Every digital PWM converter has a bandwidth and a range of input and output circuit parameters that it can control. The bandwidth of a PWM converter is complex and depends on factors such as power switch limitations, the type of control algorithm, feedback or feed-forward, sensors, and so forth.

The PWM Voltage Sourced Converter (VSC) has distinctive advantages over other converter alternatives. These include lower harmonics and 4-quadrant operation so that power factor is managed as required and converter reversible. Other options considered are the Line Commutated Converters and Cycloconverters (used for propulsion).

PWM is a powerful technology, but its use is not without sacrifice in terms of useable converter rating and, most important, increased switching losses. Also, effective use of PWM is device limited. The problem is that given the state of the art of devices, high switching frequency results in higher switching losses. During the turn-on, the forward current rises before the forward voltage falls and during turn-off, the forward voltage rises before the current falls. Simultaneous existence of high voltage and current in the device during switching is the source of switching power losses. Being repetitive, they represent a significant part of the losses. Continued improvement in these devices is essential to reducing the losses.

In classical PWM, the carrier or switching frequency must be x times the main frequency [x being a triple non-even integer (i.e., 9×60 Hz = 540 Hz for 60 Hz frequency)]. In terms of desired performance, 9 times PWM is a low-frequency PWM. At this low ratio of switching to fundamental frequencies, cosine interactions occur between the modulation frequencies and the switching frequencies. At ratios greater than 20, the cosine interactions disappear; however, switching losses increase significantly. In fact, 100 times greater will be desirable. Harmonic performance is an essential requirement. The choice is between (1) large filters, (2) high phase order involving phase shift transformers and smaller filters, or (3) PWM operation with higher switching losses and very small tuned filters and DC capacitors.

U.S. Navy Systems

A key feature of the Electric Ship concept is that all generators will be available for providing service to the ship, the weapons systems, or the propulsion loads. The rectifiers for the motor drive inverters interface directly to the ship generation bus. The connected rectifiers have to limit harmonic distortion to the bus regardless of which generators are on-line. Multiple sources of drive power will be configured to meet the wide range of ship operating modes. Different sources and amounts of drive power are required during anchor, cruise, on-station, and battle conditions. Drive rectifier accepts power from various reconfigurable generators without the introduction of harmonic distortion, as is seen on existing high power rectifiers.

Power Electronics Building Block (PEEB)

PEBB is a broad concept that incorporates the progressive integration of power devices, gate drives, and other components into building blocks that have defined functionality and interfaces that serve multiple applications. This results in reduced cost, losses, weight, size, and engineering effort for the application and maintenance of power electronics systems. Based on functional specifications of PEBBs that relate to the performance requirements of intended applications, the PEBB designer addresses to the details of the device stresses, stray inductances and switching speed, losses, thermal management, protection, measurements of required variables, control interfaces, and potential integration issues at all levels. PEBB is a generic strategic concept that incorporates several technology aspects that have been foreseen as key to major reduction in cost, losses, size, and weight of power electronics. These reductions are interrelated, with cost being the most important, while the others may lead to cost reduction up to an optimum point. To provide economic and performance rich solutions, the key technology aspects in the next generations of power electronics are

- Standard PEBB designs to cover wider market base
- Advanced devices
- Integrated packaging
- Progressive integration from device level to PEBB level
- Snubberless design
- Advanced converters that provide control of reactive power
- The ability to act as active filters
- Minimum filter requirements
- Standardized control and protection architecture
- Defined interfaces that allow “plug and play”
- Advanced interactive simulation tools.

Modular and hierarchical design principles are the cornerstones of the building block concept. The idea of open plug-and-play architecture is to build power systems in much the same way as personal computers (PCs) are built. In the long run, PEBBs may be plugged into power electronics systems and operational settings would be made automatically. The system knows the PEBB capabilities, its manufacturer, and its operational requirements. Each PEBB maintains its own safe operating limits.

Digital Controls

The overall control architecture must have the inherent capability to support the integration of these PEBBs, regardless of how they are configured together. When the control functions of many different power electronic systems are evaluated, a significant number of common functions are discovered, irrespective of the target application. Using a concept of system layers, it is possible to develop a hierarchical control architecture in terms of the required response time for the PEBB-based systems.

For discussion, consider the division of the control architecture into three layers (although in practical terms, there may be more than three layers or levels):

1. **System application level (response time 10s of ms).** The system application level determines the overall mission of the system.
2. **Function controller level (response time 100 μsec to 1 ms).** The function controller level is responsible for and maintains functions such as synchronous timing [phase-locked loop PLL)], current and voltage filtering measurements and control, and duty cycle calculations.
3. **PEBB or power electronics conversion level (μsecs depending on PWM frequency).** This level is responsible for switching or modulation control, pulse generation and gating, safe commutation [limits of di/dt (rate of rise of current) and dv/dt (rate of change of voltage) and so forth], and primary protection.

A commercially available Digital Signal Processor (DSP) can be used at each layer, and standard communication protocols can be used for information flow between the layers. The Institute of Electrical and Electronics Engineers (IEEE) Power Engineering Society (PES) Task Force is working to define a control and protection architecture for PEBB-based systems.

Soft Switching

Soft-switch inverters are an enabling technology for many high-power military applications such as DEWs (lasers, HPM), surveillance radars, aircraft electromechanical actuators, and electric motor drives for ships. Zero voltage switching (ZVS) and zero current switching (ZCS) eliminate significant power loss in the inverter, thereby increasing efficiency and reducing the size of any required cooling systems. To reduce the mass of the inverter transformer, inductors, and capacitors, switching frequencies must be in the 20-kHz to 500-kHz range. Power for future applications range from tens of kilowatts for actuators to up to tens of megawatts for DEWs and ship motor drives. Over the next 20 years, inverters will produce output voltages from hundreds of volts up to hundreds of kilovolts, with simultaneous input currents from tens of amperes to thousands of amperes. As the power and energy of conversion equipment increases, soft-switching topologies will become increasingly important.

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MCTL DATA SHEET 7.1-2. THERMAL MANAGEMENT

Critical Technology Parameter(s)	Management of heat generation so that any increased temperature does not (1) create frailty in conductors and interconnects, (2) cause rapid aging and deterioration of insulators or adjacent components, or (3) cause excess heat to create an IR signature sufficient to increase the likelihood that the system will be detected or targeted in its operating environment.
Critical Materials	Highly thermally conductive materials (mostly metals) are critical to proper thermal transfer. Heat spreaders, heat sinks, fans/blowers, chilled air, cryo-coolers, heat exchangers, and liquid coolers are tools for managing temperature rise on components and assemblies. Applying these tools, making prudent technology selections, and understanding system-cooling architectures are critical to thermal management.
Unique Test, Production, Inspection Equipment	Leak detectors; thermal chambers; temperature sensors.
Unique Software	Software programs such as those from Fluent, Inc., are useful in thermal design.
Major Commercial Applications	Commercial and military electronic systems have the same issues; however, because of the military's dense packaging requirements and environmental conditions, the military's design approaches can be different from those of commercial electronics. Also different is the military's issue of high-power dissipation, which complicates thermal management issues.
Affordability Issues	Cost is critical in commercial electronics because of the low margins in the industry, but the trend in industry is toward higher density packaging to make cooling more compatible with that of military systems. Thermal management improvements in the commercial sector will eventually translate into cost reductions in the military sector.
Export Control References	WA Cat 6; USML XX; CCL Cat 6.

BACKGROUND

Thermal management is critical for maintaining acceptable temperature levels for electronic equipment. Thermal management is made up of multiple individual technologies, each one critical for maintaining a high-reliability system/unit with proper cooling.

Heat is the second largest cause of failure in electronic equipment. Heat shortens the life of electronic components if it is beyond acceptable design levels. Managing the flow of heat away from critical components is key to extending the life of an electronic assembly. Integrating the system cooling with the energy/power system cooling is extremely important. Direction of airflow, if not properly designed at the system level, can add heat rather than remove heat. Cost effectiveness can be improved with system cooling approaches rather than subassembly individual cooling methods.

MCTL DATA SHEET 7.1-3. INTERCONNECTIONS

Critical Technology Parameter(s)	Interconnection criticality is defined by the ability to maintain low-resistance interfaces reliably throughout operations. This applies to removable and nonremovable electrical interfaces. For removable connectors, contact force is critical for successful operation. Gold contacts require between 30 and 40 g of contact force. Tin lead requires 100 g of contact force. Contact physics is critical to solid and reliable design.
Critical Materials	Critical to reliable interconnections are compliant materials, mostly metals such as berilium, copper, phosphor, bronze, and brass. Also critical are material finishes such as gold and, in some instances, silver.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Removable and nonremoveable connectors are critical to the operation of interconnections. The commercial market has the same reliability concerns as the military.
Affordability Issues	The cost of interconnections ranges greatly since the range of operation is so great (milliamps to megaamps). Volumes of the lower current connections are significantly greater than application-specific high-current connections so they are more cost effective and cover more markets.
Export Control References	WA Cat 3 and 4; CCL Cat 3 and 4.

BACKGROUND

Interconnections fall into two types: removable and nonremovable electrical interfaces. Interconnections, historically, have been the largest single cause of failure in electronic equipment. This is especially true of removable connections (electronic connectors).

Removable interconnections include pluggable, zero insertion force (ZIF) connectors, and low insertion force (LIF) connectors. For these types of connections, modes of failure include fretting corrosion, greater/lesser pin forces, vibration, and shock. Occasionally, misalignment of pins (contacts) could result in failure. The use of this type connector is for removable assemblies such as field replaceable units (FRUs) and systems that require subassemblies that can be added at a time other than initial assembly.

Nonremovable interconnections include soldered/welded joints, bolted joints, and ultrasonically bonded and high-pressure compression processes. Theses type of interconnection are primarily used for high-current applications and generally are more reliable than removable connectors.

MCTL DATA SHEET 7.1-4. AIRBORNE ELECTRIC POWER

Note: *Technologies supporting this system are included in additional data sheets.*

Critical Technology Parameter(s)	An architecture that distributes power to be collocated with loads; combinations of items such as starter generators so that electricity is produced and managed with a minimum number of components; aircraft power at a voltage and power level driven by the needs of the using system.
Critical Materials	High-temperature superconducting materials, including AC-tolerant material.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Applicable to commercial aviation, power utilities, and (electric) automotive applications.
Affordability Issues	Military-specific parts for power systems are expensive. Suitability of commercial parts is investigated to help mitigate costs of electric systems. Although electric-powered subsystems may have higher procurement costs than conventional approaches, system-level cost benefits are achieved when considering life-cycle costs and reliability while enabling a warfighting capability.
Export Control References	WA ML 10;[1] USML VIII.

BACKGROUND

Lightweight, compact power systems that have ratings from hundreds of kilowatts to several megawatts are required on airborne platforms. Technologies include advanced power generation, distribution, control, energy storage, and thermal management to ensure the survival of platform and mission capability. Electric technologies will enable airborne-DEWs.

In the early 1990s, the U.S. Air Force formulated the MEA initiative, which embraced the concept of using electrical power for driving aircraft subsystems that are typically driven by a complex hybrid of pneumatic, hydraulic, mechanical, and electrical power. The MEA initiative emphasized the use of electrical power instead of hydraulic, mechanical, and pneumatic power for optimizing an aircraft's warfighting capability and life-cycle costs. Today "more electric" systems are becoming a mainstay, whether in aircraft, automobiles, or ships. Since the 1990s, the focus has been on the "more electric." The future will be focused on the "all electric."

[1] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.1-5. SHIPBOARD ELECTRIC POWER

Note: *Technologies supporting this system are included in additional data sheets.*

Critical Technology Parameter(s)	Any integrated electric warship propulsion and weapon/sensor system having any of the following characteristics and specifically designed components for integrated power generation, power distribution, and energy storage for shipboard weapon and sensor systems with: 1. Power density on the order of 10 KW/LT ship displacement (40- to 50-percent weight and volume reductions over conventional propulsion motors). **Note**: *LT is an acronym for long tons. A long ton is 2,240 pounds.* 2. Specific fuel consumption (SFC) on the order of 0.4 lb/(hp*hr). 3. Electric motor controllers with the waveform fidelity required to meet platform-protection signature objectives. 4. Flexibility of shifting of high power between propulsion and weapon and sensor system loads. 5. The ability to provide adequate power for capability to give persistent strike, interdiction, suppression, and other fire support missions for ground and expeditionary forces at ranges up to 200 nm with an EML (railgun). 6. The ability to supply power to DE systems for ship defense against Antiship Cruise Missile (ASCM) and asymmetrical threats.
Critical Materials	Dielectric and polymer materials for high-power capacitors; SiC technologies for high-power switches; materials offering enhanced thermal management properties for system heat dissipation or capacity; rechargeable Lithium/Lithium-Ion (Li/Li-Ion) batteries and solid polymer electrolyte technology in “large” cells; materials that can handle EM rail wear, thermal management, and electric transitions.
Unique Test, Production, Inspection Equipment	Components that require specially designed tests and calibration start at the component level all the way through entire ship testing. This includes component factory tests, component shock and vibration testing, full set of land-based system testing, system tests on ranges when required leading to a full sea trial followed by a full at-sea life fire shock test.
Unique Software	Software specially designed or modified to meet militarily critical parameters; source code for system overall doctrine and control; algorithms and verified data needed to control electric warship systems from power generation to the end of the muzzle, laser aperture, or sensor.
Major Commercial Applications	Prime movers such as gas turbines and diesels along with the power generation components such as propulsion motors, controllers and power electronics have wide application in the private sector cruise ship industry. However, the higher power densities required on warships because of size restrictions and higher power requirements make current commercial propulsion motors, power electronics, transformers, rectifiers, and inverters sub-optimal to impractical. All portions of the PFN, such as energy storage, high-speed switching, coax bus burs, and rectifiers for high-power loads, should be considered noncommercial.

Affordability Issues	Military-unique high-power, high power-density devices will continue to be significantly more expensive than commercial systems because of smaller production volumes and more stringent operational requirements. As commercial vessels adopt podded electric propulsion, cost will decrease.
Export Control References	WA ML 9;[2] WA Cat 8; USML VI; CCL Cat 8.

BACKGROUND

An electric warship power generation and associated PFN will enable the power heretofore trapped in the propulsion train to be made available to high-power weapon and sensor systems. Using electric power for these combat systems eliminates the need for propellant charges and high explosives for propulsion and improves the safety and consistency of the propelling energy. These steps extend the ship's fuel capacity and the number of rounds that can be stored anywhere on the ship. Using weapons such as the EM rail gun enables rapid response and a deep-strike capability, with a short time of flight from a surface ship. This increases overall lethality. Through these approaches, the ordnance for an EM rail gun allows for a deep magazine. Managed electric power also can be allocated to other DE systems.

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2 Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.1-6. GROUND VEHICLE ELECTRIC DRIVE

Note: *Technologies supporting this system are included in additional data sheets.*

Critical Technology Parameter(s)	Energy density, power density, 70 kW/L inverter efficiency > 95%, junction temperature > 110 °C, blocking voltage, avoidance of single event burnout (SEB).
Critical Materials	SiC substrates with low micropipe defect density, < .5/cm^2 for 3" diameter substrates (in production) (0.22 has been demonstrated in the lab, and 5 is available commercially). Thick SiC (100 μ) epitaxial materials with low defects.
Unique Test, Production, Inspection Equipment	High-density plasma etching, high-temperature annealing, rapid thermal annealing (RTA), high-resolution lithography, ion implantation, dielectric deposition, sputtered and evaporated metals.
Unique Software	Fault-tolerant power architecture control system software and interfaces. Active suspension control software and interface.
Major Commercial Applications	Commercial HEV batteries, commercial automotive and trucking suspensions, distributor-less electronic ignitions, and automotive engine sensors reduce or eliminate the need for cooling of engine electronics. Aircraft weight savings. Sensor amplification at point of measurement eliminates need for heavy shielding conduit for small signal transmission, industrial process measurement and control instrumentation. Reliable sensing and control in aggressive environments not currently served by solid-state electronics. Reduce size and weight of satellites and space platforms by allowing electronics to operate at higher temperature. Jet engine sensors actuators and control electronics.
Affordability Issues	Some spinoff to commercial EVs will eventually reduce military costs.
Export Control References	WA ML 6;[3] USML VII.

BACKGROUND

The concept of an all-electric combat vehicle emerged in the 1980s. It was envisioned that that all major components—armament, armor, and drive system—would be electrically powered or energized. Although this is well short of being realized, some parts of the concept have made considerable progress. In particular, electric drive demonstrators have been developed for tracked and wheeled combat vehicles. The development of electric drives for tracked vehicles has been led by United Defense, which has been involved with them longer and more consistently than any other organization. United Defense started by installing an electric transmission in an M113 armored personnel carrier (APC), a M2 Bradley Fighting Vehicle (BFV), and a U.S. Marine Corps AA7V amphibious assault vehicle (AAV). In the 1999–2002 timeframe, United Defense jointly developed the LANCER demonstrator, which was used a possible prototype for the FCS manned ground vehicle (MGV). In the past 4 years, United Defense has built three more demonstrator vehicles with hybrid electric drive: the Transformation Technology Demonstrator (TTD), the Non Line of Sight-Cannon (NLOS-C), and the Thunderbolt.

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[3] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.1-7. SOLDIER SYSTEM POWER

Note: *Technologies supporting this system are included in additional data sheets.*

Critical Technology Parameter(s)	Hybrid systems operating at specific energies in excess of 500 W-hrs/kg are likely to be exclusively military in nature. Rechargeable battery power systems operating at lower specific energies are likely to be dual use.
Critical Materials	Critical ingredients in catalysts, electrodes, and electrolytes are typically controlled as corporate proprietary information.
Unique Test, Production, Inspection Equipment	Critical production procedures are typically controlled as corporate proprietary information.
Unique Software	None identified.
Major Commercial Applications	Advances involving rechargeable batteries will continue to be of intense interest to the commercial sector for powering hand-held electronic devices.
Affordability Issues	Military-unique batteries and power systems will continue to be significantly more expensive than commercial systems because of smaller production volumes.
Export Control References	WA ML 11;[4] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Soldier Power Systems (see Figure 7.1-2) will provide the 21st century warrior with power sources that are enablers for a host of man-portable electronic devices ranging from communications and sensors to weapons. The warfighter will be the keystone of the future digitized Army. Power requirements have been estimated as high as 100 W, with a time-averaged 12 W as the current power assessment for the Future Force Warrior (FFW), with a long-term goal of reducing this to 10 W.

In the near term, batteries will power the FFW. The mid and long term will see the introduction of hybrid systems that combine high specific-energy sources such as fuel cells and other air-breathing energy sources with high power-density rechargeable batteries. Autonomous small team operation for 24 hours is the near-term objective. The long-term goal is 72 hours. For the 24-hour mission, total soldier system fighting weight is not to exceed 50 pounds for the typical rifleman. The long-term goal is 40 pounds.

[4] Including associated software and technology specified in WA ML 18, 21, and 22.

SECTION 7.2—ENERGY CONVERSION AND POWER GENERATION

Highlights

- Electrical power requirements are pervasive. The ability to deliver sustainable energy to the battlefield will be critical for future net-centric concepts of sensor operation and battle management and for certain advanced concept for armaments, active armor protection, and silent watch for signature management.
- The future battlefield will require systems supplying power at levels ranging from milliwatts to gigawatts.
- Advanced precision weapons, mobile combat systems, radar, and electronics countermeasures and communications systems are enabled through next-generation high-energy electronics systems, including the prime energy sources, power conditioning, and distribution.

OVERVIEW

Energy conversion and power generation encompass the transformation of biological, chemical, EM, nuclear, mechanical, and thermal energy or reactions into electrical power. The output may be pulsed, burst, or continuous. The future battlefield will require systems supplying power at levels ranging from milliwatts to gigawatts or even terawatts peak.

Pulsed power is generated by the inherently pulsed nature of the source, such as explosive technologies, or derived through the use of PFNs. Pulsed sources can also be used in conjunction with fast switches to provide pulses of shorter duration, higher frequency, and greater peak power. Burst is a form of pulsed power where the duration between shots (“OFF”) being much greater than duration during a shot (“ON”). Continuous power, by definition, is supplied on a continual basis by sources ranging in size from batteries to large turbines.

The new era of biotechnology has created opportunities for using biological systems or biomimetics as power-generating systems and as nanoscale motors. These electrical power systems are based on the ability of biological membranes to generate electro-osmotic gradients and proton pumps.

BACKGROUND

All military platforms are subject to volume and weight constraints. In addition, since the ability to initiate actions without awareness by any adversary is becoming more significant, the need for stealthy land, sea, and air platforms is more important. With the exception of hydrocarbon-fueled air vehicles, all others can be optimized for limited missions using electrical energy.

HEVs and all-electric vehicles will integrate traditional power-generation devices (e.g., combustion engines and generators) with power sources (e.g., batteries and fuel cells). Further, ultracapacitors and batteries have been used with regenerative braking—the process of reclaiming energy through deceleration. All-electric vehicles rely strictly on batteries for power generation, while HEVs combine batteries with other sources of power. Series HEVs use combustion engines or fuel cells to generate electric power and use electric motors to drive the wheels. Parallel HEVs take some of the power from the combustion engine as shaft power and deliver this power directly to the wheels in parallel with the electric motors. These robust platforms eliminate the use of hydraulic, pneumatic, and mechanical power, and the benefits are numerous.

Mobile platforms are important in this discussion because their subsystems require pulsed or continuous power, which is provided by the larger power-generation system. Mobility itself has its own power requirements, which vary with the motion of the vehicle. For example, acceleration requires more power than deceleration. In battle conditions, an HEV would need to provide continuous power to computer, environmental, and low-observable subsystems, radar, and mobility. Pulsed power would be required for weaponization (including HPM, lasers, EW, and

DE systems), for active protection, and for augmenting propulsion. Mobile platforms include attack vehicles and support vehicles.

Batteries

A battery is a device that converts the chemical energy contained in its active materials into electric energy by means of an electrochemical oxidation-reduction reaction. A battery can contain one or more cells, connected in series or parallel, to create the desired output voltage and energy content. The cell consists of an anode, cathode, electrolyte, and separator. The anode gives up electrons to the external circuit and is oxidized during the electrochemical reaction. The cathode accepts electrons from the external circuit and is reduced during the electrochemical reaction. The electrolyte provides the medium for the ionic transfer of electrons (cations and anions) between the cathode and anode. The separator is a physical barrier that prevents electrical and physical contact between the cathode and anode but is permeable to allow the ionic movement of electrons between the cathode and anode.[5] See Figure 7.2-1.

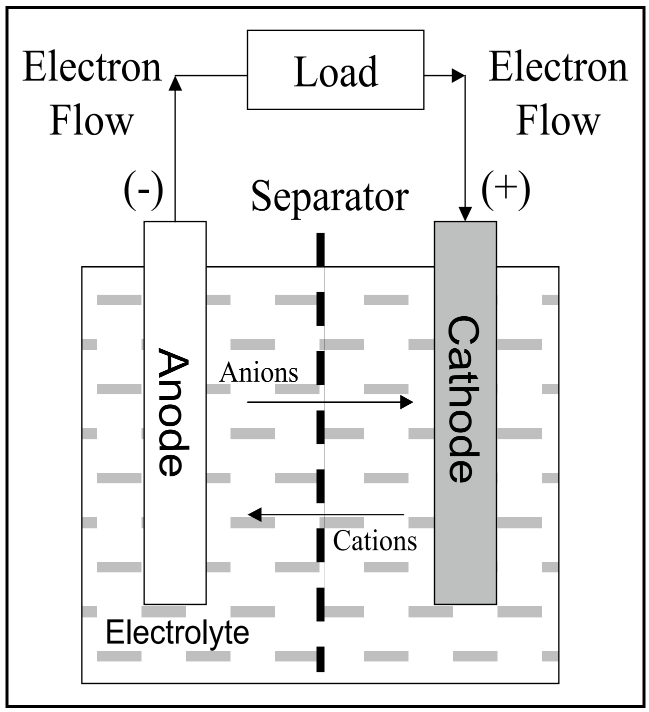

Figure 7.2-1. Sample Battery/Cell Schematic

Fuel Cell

A fuel cell is a continuous-feed electrochemical device of limited pulse-power capability. It produces electricity by oxidizing hydrogen, as illustrated in Figure 7.2-2. Fuel cells are categorized by the electrolyte that is contained within them and by their operating temperature. Air or oxygen acts as the oxidant, and hydrogen or hydrogen derived from a carbonaceous fuel is used. (Hydrogen is the simplest fuel from an operational viewpoint, with increasing difficulty in consuming more complex fuels from methanol through diesel.) However, storing hydrogen on the battlefield is difficult because it needs to be maintained at cryogenic temperatures or high pressure and is a formidable fire hazard. Table 7.2-1 lists alternatives that are being actively pursued for hydrogen storage.

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5 David Linden, *Handbook of Batteries*, McGraw-Hill, 1995.

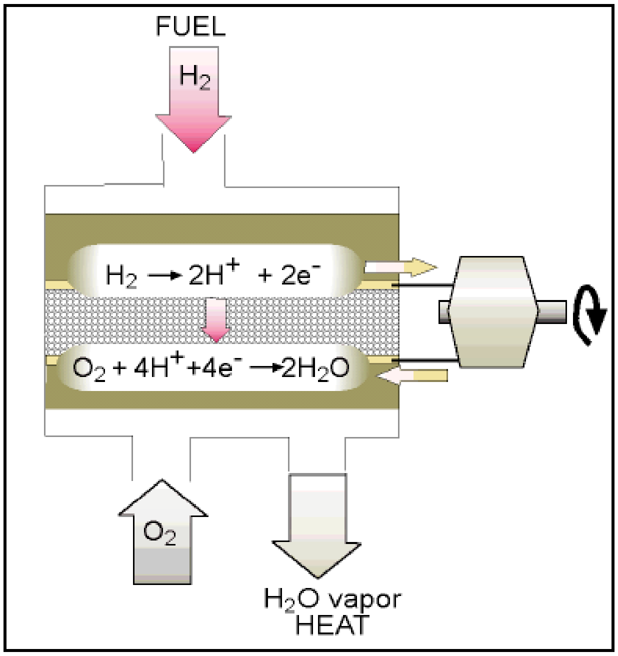

Figure 7.2-2. Fuel-Cell Schematic (Source: Army Materiel Command PEMFC ATAR, 2001 Topic)

Table 7.2-1. Hydrogen Storage Initiatives

Hydrogen Technology	Systems Goals*
Pressurized Tank Supply (Baseline)	H_2 at 2,000 to 5,000 psi 1 to 2% by weight H_2 (~ 300 W-hours/kg @4,500 psi)*
Hydrogen Stored in Glass Microspheres	H_2 at 9,000 psi ~ 4% by weight H_2 (~ 600 W-hrs/kg)*
Ammonalysis of $LiA1H_4$	Chemical reactions produce about 60 grams** of High purity H_2, ~ 6% by weight H_2 (~ 1,000 W-hours/kg)*
Hydrolysis of Organo-Silanes	
Hydrolysis of a Chemical Hydride Slurry	
Hydrogen from Liquid Fuels Direct Methanol Fuel Cell Diesel Fuel Reforming	10% by weight H_2 (2,000 W-hrs/kg)**
Hydrogen Storage in Carbon Nanofibers	Desorbs H_2 at room temperature 2 to 3% by weight H_2 (400 W-hrs/kg)*

Notes: * *1 gram of Hydrogen produces about 20 W-hrs electrical from a PEM fuel cell.*

** *W-hrs/kg are for the Hydrogen Delivery System and do not include the weight of the fuel cell.*

Photovoltaic (PV) Cells

A PV cell is a semiconductor device that directly converts light into electricity. It contains two layers of doped silicon (or other equivalents) layers. The top thin layer of the cell is composed of a silicon crystal doped with a small amount of phosphorus. The process creates free electrons within the silicon crystalline structure. The second layer is composed of silicon crystal doped with boron. The crystalline structure formed will have free void space where electrons normally exist. The phosphorus-doped silicon is negative (N-type silicon) and the boron-doped silicon is positive (P-type silicon). As light penetrates the silicon, it will force an electron out of its crystalline structure. This creates a whole electron pair. The electron has a negative charge, and the hole it leaves is positively charged. The junction between the two silicon layers will have an electrical field that prevents the holes and electrons from recombining directly.[6] (See Figure 7.2-3.)

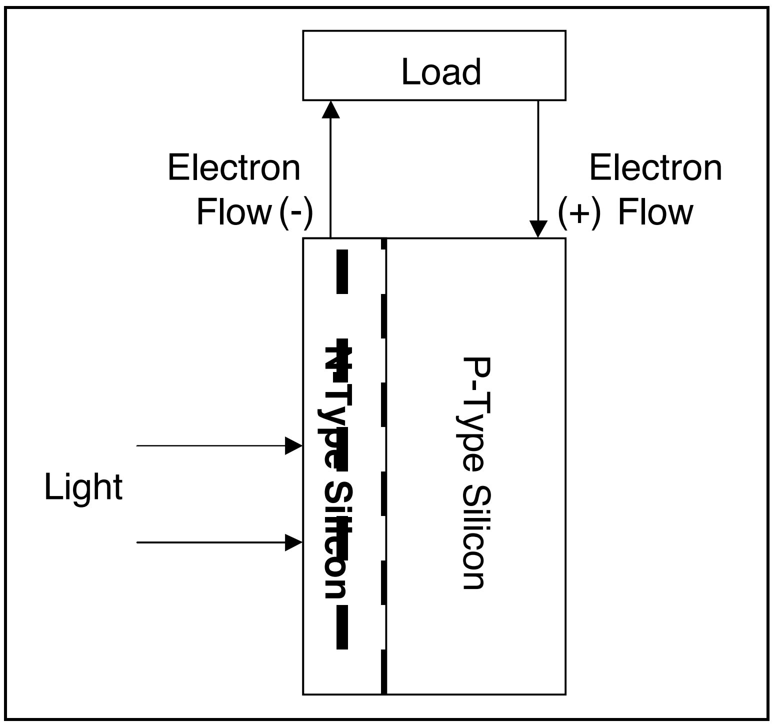

Figure 7.2-3. Sample PV Cell Schematic

Thermophotovoltaic (TPV)

TPV is a device that converts EM radiation from a thermal (nonsolar) source directly into electricity. A TPV system has five key components: the burner or heat source, the emitter, the PV cell, the filter, and the recuperator. The heat source or burner converts the chemical energy of a given fuel into heat and transfers that heat to an emitter. The emitter absorbs this energy as it is heated. This emitter then radiates the heat as light. This radiation is focused onto PV cells, which use only that energy from photons with energies over its bandgap. A filter is used to achieve spectral control and increase system efficiency. It directs that part of the radiation that matches the bandgap of the PV cell to the cell and reflects that "out-of-band" energy back to the emitter. The PV cell converts the energy into electricity. The portion of the energy that is not converted is removed as waste heat. Waste heat in the exhaust gases is recovered and preheats the combustion air through a recuperator. Hence, a recuperator is used to increase system efficiency. See Figure 7.2-4.

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6 Ed Roberton, *The Solarex Guide to Solar Electricity*, Tab Books Inc., Blue Ridge Summit, PA, 1983.

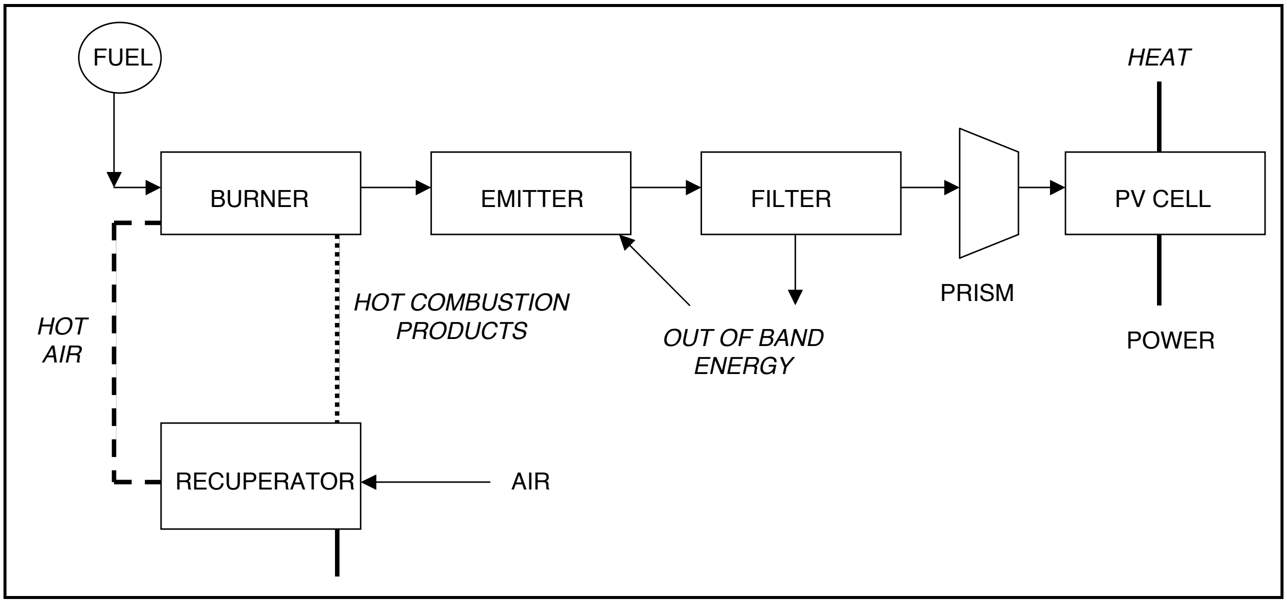

Figure 7.2-4. General Schematic of a TPV Device

Thermoelectric Generators (TEGs) (see Figure 7.2-5)

Thermoelectric power generators are devices that convert thermal energy directly into electricity through the Seebeck effect. The heat source may be a primary (fuel burner, nuclear reactor, solar furnace, and so forth) or secondary (waste heat from a vehicle or industrial process, natural temperature gradient, and so forth). A TEG system has four key components: a heat source, a TEG module, a cold-side heat sink, and the electrical load. The system may also include an active cooling system for the cold side or a voltage regulation circuit. The TEG module consists of a series of p-n couples incorporating special semiconductor materials that are optimized for the Seebeck effect. The overall efficiency of the system depends upon the efficiency of the thermoelectric material and the intrinsic and extrinsic losses across all the thermal and electrical interfaces and connections in the system.

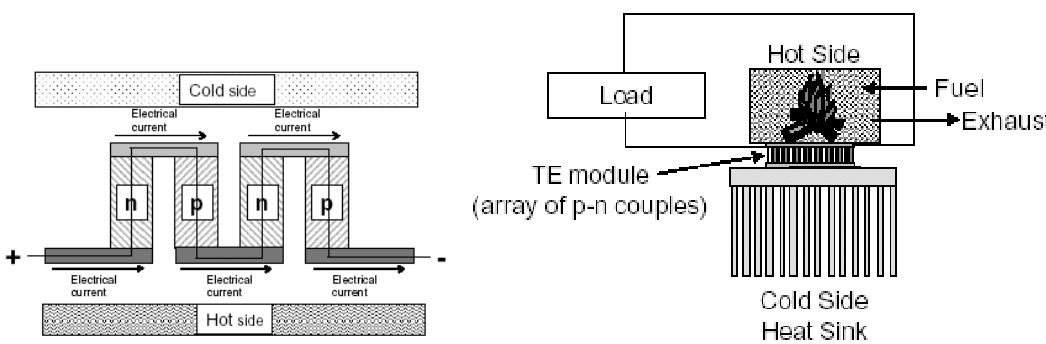

Figure 7.2-5. Sample TEG Module and Power Generator Schematic

Rotating Machinery

Rotating machines offer the potential for storage and generation of electrical energy. The key requirement for military use is a reduction in size. The DoD has had an interest in several types of rotating machines, notably in compulsators and pulsed alternators for high pulsed-power DEW and electric armaments applications, direct-drive generators for gas-turbine driven systems, and in in-hub motor/generators as an enabling technology for future ground combat systems. Rotational energy can also be stored as mechanical rotational energy in a flywheel. Because momentum (and stored energy) increases directly with the square of the angular velocity, modern systems exploit advances on composite materials to create flywheel storage systems that withstand the centrifugal forces associated with extremely high rotational speeds to increase energy density.

The market for the HEVs may increase the demand for rotating machinery—as motor/generators and as storage devices. California has enacted a series of strict emission laws that require all car manufacturers to produce zero emission vehicles (ZEVs) by the early 21st century. Among the technologies being introduced to meet these deadlines, the most viable seems to be the HEV.

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Ashok S. Patil and Richard Jacobs, "U.S. Army Small Fuel Cell Development Program." *IEEE Aerospace and Electronics Systems Magazine*, Vol. 15, Issue 3, March 2000, pp. 35–37.

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LIST OF MCTL TECHNOLOGY DATA SHEETS
7.2. ENERGY CONVERSION AND POWER GENERATION

Batteries

Fuel Cells

Rotating Machinery

Thermoelectric Generators

Photovoltaics and Thermophotovoltaics

MCTL DATA SHEET 7.2-1. LITHIUM ION (Li-Ion) (LIQUID ELECTROLYTE) RECHARGEABLE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage: 3.5 V DC (Navy 3.6 V) Energy density: 150 W-hrs/kg (Navy > 200) Power density: 300 W/kg* Cycle life: 500 or more cycles Recharge time: 3.5 hours or more Temperature range: –30 to +55°C Storage life: 5 years Cell design: Spirally wound, coin, bipolar * Saft America cells are capable of > 1,000 W/kg for HEV applications, but energy density is not as high in these designs.
Critical Materials	Lithiated carbon for anode; cobalt dioxide and nickel cobalt oxide blends for cathodes; additives for cold-temperature performance; graphite substitutes for carbon.
Unique Test, Production, Inspection Equipment	Dry room for handling of lithiated carbon anode; winding machines for cathode/anode/separator; hermetical sealing.
Unique Software	System Management Bus (SMBus) software for state-of-charge information during discharge and recharge controls; standard in laptop computers to allow device software track battery life.
Major Commercial Applications	Laptop computers; cellular phones; consumer electronics.
Affordability Issues	Procurement—approximately $1.25/W-hr; Life cycle—approximately $.005/W-hr @ 250 cycles, $.0025/W-hr @ 500 cycles. Undersea vehicle battery procurement costs are expected to be 4 to 5 times more expensive based on current projections for the Advanced SEAL Delivery System (ASDS).
Export Control References	WA ML 11;[7] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

The rechargeable Li-Ion battery is the first stable rechargeable lithium battery that is safe for consumer application. The Japanese first commercialized the Li-Ion battery in 1990 for camcorders and laptop computers. It uses a lithiated carbon anode, which is more stable during recharge than the more active metallic lithium anode. Despite its higher unit cost compared with the heavier NiMH battery packs, many high-end users preferred the Li-Ion battery for its long operating life and light weight. By 2000, the demand and production of Li-Ion cells were sufficiently large that the Li-Ion battery started to displace the NiMH batteries in terms of cost and market. Initially, Japan dominated the lithium ion market, but sufficient profits and demands for the product made other nations—particularly South Korea and China—enter as lower cost producers. The U.S. military has retrofitted and fielded several of its legacy portable rechargeable batteries with the Japanese Li-Ion cells. France is concentrating on large cylindrical Li-Ion cells for aerospace and large powerpack applications. The United States is pursuing large (greater than 300 Ah) prismatic cell designs for military applications.

[7] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-2. LITHIUM POLYMER (GEL ELECTROLYTE) RECHARGEABLE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage: 3.6 V DC Energy density: 170 W-hrs/kg (Navy > 200) Power density: 100 W/kg Cycle life: 250 or more cycles Recharge time: 3.5 hours Operating temperature: –30 to +55 °C Storage life: 5 years Cell design: Bipolar, pouch
Critical Materials	High conductivity polymer electrolytes and gels; lithiated carbon; vinyl lined foil.
Unique Test, Production, Inspection Equipment	Dry room for handling lithiated carbon anode; winding machine for cathode/separator/anode film; coating machines for gel or polymer electrolyte.
Unique Software	SMBus software for state-of-charge information during discharge and recharge controls, standard in laptop computers to allow device software track battery life. CadBus software for large EV batteries.
Major Commercial Applications	Laptop computers; cellular phones; consumer electronics.
Affordability Issues	To be provided.
Export Control References	WA ML 11;[8] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

The rechargeable lithium polymer battery is a new and emerging technology (more recent than Li-Ion batteries). It is driven by the need to make thin batteries for slim consumer electronic devices. Li-Ion cells packaged in metal cases become less energy-density efficient because the inert case weight portion of the cell design increases as the power source is made thinner or smaller. A Li-Ion battery that uses a gel or polymer electrolyte can be packaged into a vinyl-lined foil pouch because little or no vapor pressure is produced by the electrolyte during charging. The inert structure (foil pouch and tabs) represent less than 5 percent of the cell weight. The gel and polymer electrolyte do not have the ionic conductivity of liquid electrolytes and do not perform well at high discharge rates at low temperatures. The early lithium polymer cells had high energy densities but did not perform at temperatures below 0 °C. In 2002, two South Korean manufacturers were able to demonstrate a lithium polymer cell that can operate at temperatures as low as –20 °C. The U.S. military is exploring the possibility of retrofitting its legacy rechargeable batteries with the Korean lithium polymer technologies. The United States, Germany, Japan, and France are conducting research on large bipolar lithium polymer cells for EV applications or large-battery power sources.

8 Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-3. LITHIUM-IRON DISULFIDE (SPIRALLY WOUND) NONRECHARGEABLE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage 1.5 V DC Energy density 120 W-hrs/kg Power density 25 W/kg Operating temperature –20 to +55 °C Storage life 10 years Cell design Spirally wound, crimp sealed
Critical Materials	Lithium anode; grid current collector; inorganic electrolytes.
Unique Test, Production, Inspection Equipment	Dry room for handling and fabrication of lithium anode; anode/separator/cathode winding machines.
Unique Software	None identified.
Major Commercial Applications	Consumer electronics (e.g., digital cameras and MP3 Walkman).
Affordability Issues	Procurement—approximately $0.20/W-hr.
Export Control References	WA ML 11;[9] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Lithium-iron disulfide uses a lithium metal anode and a solid iron disulfide cathode. This is the only known lithium technology in production that has a 1.5-V DC and is interchangeable with devices that use alkaline cells. The product was developed in 1990 to provide the consumer with 1.5-V DC AA size lithium cell that can be used in commercial electronics that required cold-temperature operations or extended battery life. The technology did not become widespread until the late 1990s when digital cameras with liquid crystal displays (LCDs) required AA cells capable of drawing up to 0.90 A of current. Alkaline AA cells were unable to meet this need, and the demand for AA lithium-iron disulfide cells increased. The United States is the dominant leader in this technology. It has production base for the consumer market. This technology is also being leveraged by the U.S. Military for handheld devices.

9 Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-4. LITHIUM MANGANESE DIOXIDE (POUCH) NONRECHARGEABLE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage 3.0 V DC Energy density 300 W-hrs/kg Power density 75 W/kg Operating temperature –20 to 60 °C Storage life 3 years Cell design Flat pouch, hermetically sealed
Critical Materials	Lithium anode; grid current collector; inorganic electrolytes and nonflammable additives to improve low-temperature performance; nonreactive epoxies for tab to pouch seal.
Unique Test, Production, Inspection Equipment	Dry room for handling and fabrication of lithium anode; anode/separator/cathode winding machines; vinyl pouch materials.
Unique Software	None identified.
Major Commercial Applications	None, but huge potential for flat consumer electronics.
Affordability Issues	Procurement—approximately $.30/W-hr.
Export Control References	WA ML 11;[10] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Lithium manganese dioxide electrochemistry uses a lithium metal anode and a solid cathode manganese dioxide. Solid cathodes do not exert any vapor pressures like liquid cathode/electrolytes; thus, the cell is less likely to vent during abuse or defect. Solid cathodes conversely do not conduct ions as well as liquid ones at low-temperature conditions. A substantial amount of work has been done to add additives into the electrolytes and optimize the surface areas of the cathode to allow the cell to provide good power at cold temperatures. In the 1990s, the U.S. military was exploring the packaging of this low-pressure electrochemistry in a flat vinyl-lined foil pouch cell for soldier-worn power source. Most of the cell's weight is composed of energy-producing material and less than 5 percent of the weight is for the inert structure. The battery packs formed by these cells are very flat and possess high energy density compared with canned cells.

[10] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-5. LITHIUM SULFURYL CHLORIDE (SPIRALLY WOUND) NONRECHARGEABLE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage 3.5 V DC Energy density 320 W-hrs/kg Power density 75 W/kg Temperature range –30 to +60 °C Storage life Up to 1 year Cell design Spirally wound, hermetically sealed
Critical Materials	Lithium anode; grid current collector; glass-to-metal seal; inorganic electrolytes and additives.
Unique Test, Production, Inspection Equipment	Dry room for handling and fabrication of lithium anode; glass-to-metal seal welders; anode/separator/cathode winding machines.
Unique Software	None identified.
Major Commercial Applications	Power for sensors in gas and oil exploration drilling bits.
Affordability Issues	Procurement—approximately $1.00/W-hr.
Export Control References	WA ML 11;[11] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Lithium sulfuryl chloride electrochemistry uses a lithium metal anode and liquid sulfuryl chloride as the cathode and electrolyte. These batteries are available in high rate-capable D or larger spirally wound cells, which are commonly used to power the sensors in gas and oil exploratory drilling. Sulfuryl chloride is highly corrosive and will shorten the cell's shelf life. The battery packs are usually fabricated and immediately shipped to the oil platform in the field, with very little storage time. The U.S. military has investigated various additives that will enhance the storage life of the cells at room-temperature storage.

[11] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-6. LITHIUM SULFUR DIOXIDE (SPIRALLY WOUND) NONRECHARGEABLE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage 3.0 V DC Energy density 160 W-hrs/kg Power density 50 W/kg Operating temperature –40 to 60 °C Storage life 5 years Cell design Spirally wound, hermetically sealed
Critical Materials	Lithium anode; grid current collector; glass-to-metal seal; balanced cell design.
Unique Test, Production, Inspection Equipment	Dry room for handling and fabrication of lithium anode; glass-to-metal seal welders.
Unique Software	None identified.
Major Commercial Applications	Survival radios for commercial/private boats; special industrial applications.
Affordability Issues	Procurement—approximately $.30/W-hr.
Export Control References	WA ML 11;[12] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Lithium sulfur dioxide electrochemistry uses a lithium metal anode and liquid sulfur dioxide as the cathode and electrolyte. This technology was developed during the early 1980s as a stable higher power source that uses lithium as an anode to replace the Vietnam-era magnesium batteries.

[12] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-7. LITHIUM THERMAL RESERVE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage: 1.6 to 2.2 V DC Energy density: 11 to 43 W-hrs/kg Power density: Up to 1,700 W/kg Activation time: 0.1 second or less Operating temperature: Up to 700 °C Storage life: 15 or more years Cell design: Sealed plate
Critical Materials	Better cathodes; electrolytes; insulation materials and heat sources; thermal management systems; squib activators; molten salt electrolytes; separators that tolerate high temperatures; boron nitride fibers and felts.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability Issues	Cost-to-performance ratio considerable (i.e., expensive).
Export Control References	WA ML 11;[13] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Thermal batteries were developed in the 1940s and widely used in military ordnances such as rockets, projectiles, bombs, mines, missiles, decoys, jammers, torpedoes, space exploration systems, emergency escape systems, and similar systems. Thermal batteries are composed of an alkali or earth metal anode, a fusible salt electrolyte, and a metal salt cathode. The battery is inert at room temperature and, subsequently, has a long shelf life of 10-plus years. The battery is integral to the weapon systems pyrotechnics. It is activated from the high temperatures generated by the application or an internal battery heating pellet. The high temperatures melt the electrolyte and cathode salts, activating the battery. In 1975, lithium and lithium alloys were introduced as anodes. This improvement allowed the battery to be subjected to internal operating temperatures up to 700 °C, with little or no degradation to its performance and provide power up to 1 hour.

[13] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-8. NICKEL METAL HYDRIDE (NiMH) RECHARGEABLE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage: 1.2 V DC Energy density: 60 W-hrs/kg Power density: 130 W/kg (AF 750) Cycle life: 250 cycles minimum Recharge time: 2 hours minimum Temperature range: –30 to 60 °C Storage life: > 3 years [Army 5 yrs] Cell design: Sealed, spirally wound or sealed plate
Critical Materials	Nickel oxide; metal hydride.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Spirally wound cells—handheld appliances and tools, consumer electronics, and remote control (RC) toys.
Affordability Issues	Purchase—approximately $1.30/W-hr; life cycle—$.005/W-hr @ 250 recharges; $.003 @ 500 recharges.
Export Control References	WA ML 11;[14] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

NiMH cells were introduced in the 1990s to replace the nickel cadmium batteries because of environmental regulations pertaining to the use of toxic cadmium metals. Its introduction helped increase the operating time of laptops and camcorders by 50 percent because of its higher energy content than the original nickel cadmium battery packs. The new battery's dominance was short lived, however, because the introduction of lighter and longer operating Li-Ion batteries also occurred at the same time. NiMH batteries were originally less expensive than the Li-Ion batteries, but the consumer preferred the lighter battery despite its higher cost. By 2000, most laptop, cell phones, and camcorders were equipped with Li-Ion batteries. As more Li-Ion batteries have been used, the price of the Li-Ion batteries has dropped to be competitive with NiMH battery packs.

[14] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-9. SILVER ZINC OXIDE RECHARGEABLE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage: 1.8 V DC Energy density: 100 to 250 W-hrs/kg Power density: Up to 1,000 W/kg Cycle life: 25 to 500 cycles Recharge time: 10 hours Operating temperature: –40 to 55 °C Storage life: 5-plus year (cell and electrolyte separate) Cell design: Prismatic plate or bipolar
Critical Materials	Electrolytic-grade silver foils, powders, and fibers. Additives (discovered by Russia) may increase cycle life.
Unique Test, Production, Inspection Equipment	Recycling facility for silver content in electrode.
Unique Software	None identified.
Major Commercial Applications	Commercial space and aerospace.
Affordability Issues	Procurement—up to $25.00/W-hr; $1.00/W-hr @ 25 cycles.
Export Control References	WA ML 11;[15] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Silver zinc batteries use a silver oxide electrode, zinc electrode, semi-permeable separator in potassium hydroxide electrolyte. The first battery was demonstrated in 1800, and the first workable battery was developed in the 1880s for electric cars. In 1941, a semipermeable separator that prevented dendrite shorts during cycling was developed, which made the battery safe and viable for commercial applications. During World War II, the U.S. military needed a power source that was compact and capable of providing high-rate discharge that would exceed the performance of lead acid and nickel cadmium batteries for powering torpedoes and other military ordnances. The silver zinc battery was one of the solutions.

The battery is a mature and well-established technology and has a limited, mostly military/aerospace market because of its high cost. Little progress or advancement is expected by 2005. Military applications include tactical aircraft, missiles, ballistic missiles, satellites, munitions, torpedoes, submarines, unmanned undersea delivery vehicles, communications equipment, and emergency pulsed-power systems.

[15] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-10. THERMAL RESERVE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage: 2.2 to 3.3 V DC Energy density: Up to 4.6 W-hrs/kg Power density: Up to 3,100 W/kg Operating temperature: Up to 700 °C Storage life: 10 or more years Cell design: Sealed plate
Critical Materials	Calcium, magnesium anode materials; fusible molten salts; metal salt cathode (chromates, metal oxides, sulfides); pyrotechnic powders.
Unique Test, Production, Inspection Equipment	Dry room and production facilities to handle flammable metals.
Unique Software	None identified.
Major Commercial Applications	Commercial space applications and systems.
Affordability Issues	Very expensive.
Export Control References	WA ML 11;[16] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Thermal batteries were developed in the 1940s and have been used in military ordnances such as rockets, projectiles, bombs, mines, missiles, decoys, jammers, torpedoes, space exploration systems, emergency escape systems, and similar systems since 1947. Thermal batteries are composed of an alkali or earth metal anode, a fusible salt electrolyte, and a metal salt cathode. The battery is inert at room temperature and, subsequently, has a very long shelf life (10 plus years). The battery is integral to the weapon systems pyrotechnics and is activated from the high temperatures generated by the application or an internal heating pellet. The high temperatures will melt the electrolyte and cathode salts, activating the battery. The battery will provide power up to 10 minutes.

[16] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-11. ZINC AIR NONRECHARGEABLE BATTERY

Critical Technology Parameter(s)	Nominal cell voltage 1.4 V DC Energy density 400 W-hrs/kg Power density 25 W/kg Operating temperature –20 to 55 °C Storage life 5 years Cell design Flat coin or flat plate cell
Critical Materials	Zinc anode; hydrophilic Teflon membranes; thin efficient air cathode.
Unique Test, Production, Inspection Equipment	Dry room for handling and fabrication of zinc anode; sealing and packaging zinc air power sources
Unique Software	None identified.
Major Commercial Applications	Hearing aids and consumer electronics for coin cells.
Affordability Issues	Procurement—approximately $15/W-hr.
Export Control References	WA ML 11;[17] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Zinc air cells use a zinc anode and thin efficient air cathode. Air is required to activate this battery. The battery has very high energy densities and is lightweight. The first successful zinc air battery was developed in 1932. The development of fluorocarbons as a polymer class in the 1970s resulted in a very thin, efficient air cathode, which, in turn, lead to the first successful zinc air coin cell for commercial use in 1977. The cells were commonly used for hearing aids. Several private ventures attempted to develop a large flat zinc air pack for laptop computers, which would be used instead of the heavy nickel cadmium/metal hydride packs available during the late 1980s. This technology (zinc air pack) was not successful because the consumer preferred the new lightweight and convenient rechargeable Li-Ion batteries that were introduced to laptops during the same period. In the late 1990s, a commercial Israeli company attempted to develop large flat plate zinc air cells for cellular phones. This venture failed in 2001, but the U.S. Army leveraged the R&D efforts to develop a high-energy, moderate-power-capable zinc air battery pack for the Advanced SINCGARS Improved Product (ASIP) man-pack radio and forward area recharging power source. The U.S. Marine Corps and the U.S. Army fielded the first zinc air battery pack in 2002.

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17 Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-12. DIRECT METHANOL FUEL CELL (DMFC)

Critical Technology Parameter(s)	Specific power 15 W/kg Power density 15–20 W/cc Total power 0.5 to 200 W System efficiency 20% Operating temperature 80 to 100 °C Service life (hours) or (cycles) 4,000 hours
Critical Materials	Catalysts; anodes; electrolyte membrane (crossover issue).
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Similar to PEMFC. Cell phones; computers; PDAs.
Affordability Issues	High cost is caused by more platinum; uses two to three times more than a proton exchange membrane (PEM). Costs cannot be driven down until a market is established.
Export Control References	WA ML 11;[18] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Currently, car manufacturers are engaged in the development of ZEVs, with the so-called indirect methanol membrane fuel cells consisting of a methanol reformer plus a PEMFC [Energy Ventures, Inc. (EVI) of Canada]. However, the methanol reformer causes many technical problems. Thus, many car manufactures are now focusing on the development of fuel cells that run on methanol and its derivatives. This trend is driven by methanol's liquid fuel characteristics, which allow for an easily transported and converted energy, especially relative to liquefied gas (high-pressure gas).

The goal for this technology is to produce portable fuel cells that will rival current conventional power supplies while achieving lower environmental impact and lower cost per kilowatt. Because of methanol's worldwide availability and its room temperature liquid state, DMFCs offer this opportunity. However, DMFC may only find applications in small portable devices (cell phones, PDAs, single-device Soldier Power applications, less than 5 W sources) because their use in transportation is still in question.

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[18] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-13. SOLID OXIDE FUEL CELL (SOFC)

Critical Technology Parameter(s)	Specific power 100 (kW/kg) Total power 20 (kW) Operating temperature 600 to 1,000 °C Efficiency 70–75% Cell efficiency 45% Operating temperature > 1,000 °C Service life (hours) or (cycles) 10 to 20,000 hours
Critical Materials	High conductivity electrolytes; materials for seals or seal technology; light fuel/oxidant storage; high-performance electrodes; improved catalysts.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	EVs; on-site power; residential power; cogeneration; thermal power plants.
Affordability Issues	Expensive but has lower fuel cost than a gas turbine.
Export Control References	WA ML 11;[19] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

An SOFC consists of three main solid parts: the anode, a cathode, and an electrolyte. The anode and cathode are porous and allow only certain gases to pass through them. Between the two is an electrolyte (which conducts electricity) that will only allow oxygen ions to pass through from the cathode to the anode. The oxygen ion combines with hydrogen to form water, heat, and electricity. As the oxygen ion passes through the electrolyte, the resulting excess of electrons on the anode side completes an electrical circuit through an external load to the electron-deficient cathode side and produces an electrical current.

Because SOFCs operate at high temperatures, they are typically insulated, which adds volume to the overall package. Also, because of this requirement, start-up times from a cold condition tend to be long—on the order of hours.

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[19] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-14. ELECTRIC MACHINES

Critical Technology Parameter(s)	Specific power continuous 2.5 kVA/kg Power density continuous 70 kVA/L Specific power peak 3.5 kVA/kg Power density peak 100 kVA/L Total power 250 kVA at 2.5 kVA/kg or higher specific power System efficiency 95% Activation time 0.2 sec Operating temperature 300 °C
Critical Materials	High-saturation, high-permeability, low-loss soft magnetic steels with good mechanical properties; permanent magnets with high-energy product and remenance; high-temperature (> 250 °C) electrical insulation systems; practical high-temperature (> 250 °C) permanent magnets.
Unique Test, Production, Inspection Equipment	Balancing equipment capable of working at high speeds > 30,000 rpm; > 250 kW drive stands (dynamometers) for generator development and testing.
Unique Software	Generator control algorithms to optimize transient response and system power quality; sensorless control algorithms; turbine engine control algorithms (i.e., logic embedded in the engine's digital control system) developed to support large shaft power extraction.
Major Commercial Applications	Technology has applicability in aerospace auxiliary power units, aircraft power systems, ground power units, and possibly high-speed machining equipment.
Affordability Issues	Prices will continue to be high because of military-specific applications.
Export Control References	WA ML 11 and 17;[20] USML XI; CCL Cat 8.

BACKGROUND

The term "Electrical Machines" refers to electric motors and generators that convert between electrical and mechanical power. A motor converts an electrical power input to mechanical power output, and a generator converts mechanical power to electrical power. The two applications are nearly identical in construction and performance, and some machines can be designed to provide motoring and generating functions. The machines are further classed by their I/O current type (AC or DC) and their means of creating the interacting rotor/stator magnetic fields. Electric machine types for military applications include permanent magnet, induction, synchronous, and switched reluctance, among others.

In typical military electrical power generation systems, a generator is driven by the prime mover, which also provides motive power for the vehicle. Another form of power generation is where the prime mover's function is to drive only the generator. This stand-alone power source is an auxiliary power unit (APU) when it is used to provide power to the secondary electric power system or to provide the starting power of a vehicle's prime mover. Military requirements in power output linked to available installation space will often dictate higher levels of power density (kW/L), specific power (kW/kg), reliability, and maintainability than are commercially available. Aerospace applications are the most demanding military application from a weight and volume standpoint.

Higher power densities are typically achieved with higher machine rotating speeds. This reduces the torque requirement and machine size for a given desired power level. Higher power densities, however, can also increase unit heat generation (kW/kg), which must be addressed with proper loss control and cooling techniques to prevent exceeding maximum material temperatures and to ensure the machine's mechanical and structural integrity. The

[20] Including associated software and technology specified in WA ML 18, 21, and 22.

machine controls can also contribute significantly to the machine system's overall weight, and higher machine operating speeds may also result in higher controller component temperatures through higher operating frequencies.

MCTL DATA SHEET 7.2-15. THERMOELECTRIC CONVERTERS

Critical Technology Parameter(s)	This power source, even with its low efficiency (converter efficiency ~ 5%) works with extraordinary reliability to supply power and heat as a supplement. No moving parts or induced corrosion is associated with this power source.
Critical Materials	Materials yielding average (not peak) ZT > 2.5 overall, 100 °C temperature range (e.g., 300 °C to 400 °C); any reported (peak or average) ZT > 3.0. (ZT = thermoelectric figure-of-merit).
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Remote unattended power supply (power generation; automotive atmospheric control (cooling and heating).
Affordability Issues	At low performance (low efficiency), thermoelectrics is not an affordability issue (e.g., thermoelectrics picnic coolers). However, high-performance thermoelectric converters will require more exotic materials and manufacturing (micro and nanofabrication) that will drive up costs significantly. The ability to make a bulk high-performance thermoelectrics material would mitigate this issue.
Export Control References	WA ML 11;[21] USML XI.

BACKGROUND

Thermoelectric energy conversion can be divided into (1) power generation from a heat source and (2) cooling from applying current through a thermoelectric device. Thermoelectric energy converters are robust and solid state and can be used for vibration- and noise-free power generation from thermal sources for main or auxiliary power or for the remote unattended electrical power supply of autonomous systems. Thermoelectric coolers are used in a wide variety of applications near (within about 100 °F) room temperature. Practical thermoelectric generators and coolers became possible in the 1950s with the production of pure semiconductor materials. Since that time, generator efficiencies have been generally low (below 10 percent). However, advances in nanostructured and thin-film devices in the last 10 years have the potential to increase these efficiencies. By 2014, converter efficiency is projected to be 15 percent. For some general references on thermoelectric material research, see the reference list at the end of this Data Sheet.

REFERENCES

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[21] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.2-16. PHOTOVOLTAICS (PVs)

Critical Technology Parameter(s)	Crystalline multijunction cells—efficiency: 26% at beginning-of-life (BOL) Thin-film solar arrays are flexible, lightweight, and low cost PV blankets supported by a lightweight structure. Critical parameters are • Specific power: 150 W/kg • Blanket cost: < $100/W.
Critical Materials	Semiconductor material names can be mentioned [i.e., gallium arsenide (GaAs), gallium indium phosphide (GaInP), and so forth], but specific semiconductor growth and solar cell device processing techniques may be classified if government and proprietary if commercial. Also, parameters such as layer thickness, doping densities, and Metal Oxide Chemical Vapor Deposition (MOCVD) growth gases, growth temperatures, and growth times may be classified if government and proprietary if commercial.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	High-power communication satellites; remote operations; village power; recharging batteries.
Affordability Issues	Increased solar cell efficiency results in smaller array size, mass and stowed volume requirements, in turn resulting in reduced system and launch costs. Thin-film solar cell technology will enable a substantial cost reduction in solar arrays. The process for manufacturing thin-film solar cells in sheet form costs much less than the current practice of manufacturing individual cells and then electrically interconnecting them and bonding them onto a substrate.
Export Control References	WA ML 11 and 18;[22] USML XI.

BACKGROUND

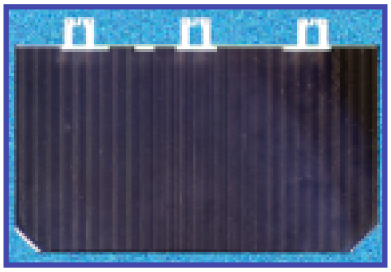
Since the early 1960s, the paramount goal of the solar cell community has been to improve the solar-to-electrical energy conversion efficiency of solar cells. The size, mass, and cost of conventional satellite space power systems depend strongly and directly on this efficiency. A high solar cell energy conversion efficiency is desired to reduce the area of a solar cell array, thereby enabling a greater payload mass and reduced launch vehicle costs. For example, an end-of-life (EOL) electrical power requirement for a typical geosynchronous communications satellite might be 10 kW or more. Since the air-mass-zero (AM0) solar energy flux in space is 1.35 kW/m^2, the 10-kW electrical power requirement would require a solar array panel area of about 50 m^2 when using 20-percent-efficient solar cells.

However, by increasing the solar cell efficiency to 30 percent, the same 10 kW electrical power requirement could be met with a solar array panel two-thirds the area and weight. Achieving such high efficiencies requires the use of multijunction cells. Progress toward the development of multijunction solar cells was first reported in the 1980s. In 1994, a two-junction indium gallium phosphide/gallium arsenide (InGaP/GaAs) solar cell was disclosed, with an energy conver-

22 Including associated software and technology specified in WA ML 18, 21, and 22.

sion efficiency of 29.5 percent for incident light from the sun at 45 degrees above the horizon (denoted as AM1.5). In 1996, a three-junction indium gallium phosphide/gallium arsenide/germanium (InGaP/GaAs/Ge) solar cell was disclosed, with an AM0 (space solar spectrum) energy conversion efficiency of 25.7 percent. In 2003, triple junction solar cells are commercially available at an efficiency of 28 percent.

Recently, triple junction solar cells have been modified for use in terrestrial concentrator systems. Under the terrestrial solar spectrum, 1 kW/m^2, the triple junction solar cell has achieved greater than 32-percent efficiency. Under concentrated sunlight, efficiencies of greater than 34 percent have been achieved.



Low cost thin-film PVs are comprised of polycrystalline or amorphous materials deposited on inexpensive substrates in high-volume, roll-to-roll production processes. These types of solar cells, because of their low cost, were originally developed for terrestrial applications and were usually deposited on glass substrates. The drive to exploit the flexible, lightweight, and low-cost nature of thin-film solar cells for space applications led to the development of copper-indium-gallium-diselinide (CIS) and amorphous silicon (a-Si) solar cells on flexible metal foil substrates. More recently, the advantages of monolithic integration and lighter mass have led to the development of thin-film solar cells on polymer substrates, including high-temperature substrates that can withstand the 500-degree processing temperatures required for CIS processing. Thin-film solar modules are manufactured on 1 mil-thick stainless steel and 1 mil-thick polymer substrates for lightweight, portable battery charging units.

Table 7.2-3 lists the performance of various cell technologies.

Table 7.2-3. Cell Technology Performance

				Efficiency (%)	
Cell Technology	**Commercial Availability**	**Cost**	**Power Density (W/cm^2) AM0**	**AM0 (space spectrum)**	**AM1.5 (terrestrial)**
Amorphous silicon	Yes	Low	122	9	12
Polycrystalline silicon	Yes	Low		N/A	14
Single-crystal silicon	Yes	Med	243	18	20
Crystalline multijunction	Yes	High	378	26	32
Indium phosphide	No	Very High	230	17	17–18
Copper indium diselinide	Yes	Low	203	15	19
Concentrator array	Limited	High	405	30	34

MCTL DATA SHEET 7.2-17. THERMOPHOTOVOLTAICS (TPVs)

Critical Technology Parameter(s)	Overall conversion efficiencies > 20%. Overall area power densities > 0.5 W (electric)/cm^2. 0.5 to 0.6 eV bandgap diode efficiencies > 30%. Spectral efficiency (angle of incident weighted up to 20 μ) or use > 80%: • Below bandgap reflectivity > 95% (below bandgap emmisivity < 0.05) • Above bandgap reflectivity < 15% (above bandgap emmisivity > 0.85).
Critical Materials	The enabling technology for high-efficiency TPVs is the development of spectral control. Current high-performance filters use antimonide selenide (SbSe) as a high-index material, yttrium fluoride (YF) as a low-index material, and zinc sulfide (ZnS) for binding layers to form a quarter wave stack interference filter on top of an indium phosphide arsenide (InPAs) plasma filter.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	No major commercial applications exist for this technology. Some small niche applications may exist (e.g., systems to provide electrical power from combustions sources for homes in the country that do not have access to an electrical distribution infrastructure).
Affordability Issues	The manufacturing methods [e.g., molecular beam epitaxy (MBE), organometallic vapor phase epitaxy (OMVPE)] for high-performance cells and filters are expensive. Bulk crystal TPV devices [e.g., gallium antimonide (GaSb)] are less costly but also less efficient. A bulk crystal that maintains the performance advantages of the epitaxial material would be truly enabling.
Export Control References	WA ML 11;[23] USML XI and XIII.

BACKGROUND

TPV energy conversion is the direct conversion of an IR heat source to electricity. A TPV direct energy conversion system is essentially the same as PV conversion of solar energy except that the radiation heat source is from a heated radiator at temperatures in the range of 800 °C to 1,700 °C.

TPV consists of a blackbody radiator emitting photons across a fixed gap (on the order of 2 to 4 mm) to a semiconductor TPV diode with a certain bandgap. Energy from the radiator above the bandgap of the TPV diode is sufficient to produce electricity that can be collected at the diode junction and passed through a load. Energy below the bandgap of the diode will be wasted as heat in the diode unless it is recuperated by the radiator. If the energy is not recuperated by the radiator, the conversion efficiency will be low. This aspect of the TPV energy conversion process is known as spectral control. The most common form of spectral control is a filter that is placed between the radiator and the semiconductor diode. The TPV diode and filter operate at cold temperatures (25 °C to 100 °C). For more information, including a basic schematic of an TPV system, see the October 1998 issue of the *Compound Semiconductor* article "Technology Update—Thermophotovoltaics" or the September 1998 issue of *Scientific America* article "Thermophotovoltaics."

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[23] Including associated software and technology specified in WA ML 18, 21, and 22.

SECTION 7.3—ENERGY STORAGE

Highlights

- Energy is stored chemically, mechanically, or electrically, with durations of microseconds to years.
- Fast-storage devices are militarily critical for weaponry.
- Storage density is becoming more important in electronic systems.
- Thermal management is critical to capacitor life and performance.

OVERVIEW

This section of the MCTL addresses technologies for long-term and intermediate storage of energy. Intermediate storage is typically used to store energy from a primary power source to support pulsed-power applications, typically at low repetition rates (less than 1.0 pps) or short bursts of multiple pulses over a short time span, with low duty cycle. The key to the design is matching the charging characteristics (i.e., the rate, voltage, and current levels at which primary power source can deliver the energy to the load) to the characteristics of the storage subsystem and matching the output of the storage to the system load. In most cases, an additional stage of power conditioning and distribution (such as an integrated pulse-forming network and/or pulse transform will be required to match the final load requirements in pulse power applications.

Storage media addressed in this section include capacitive stores (devices and integrated capacitive stores) and mechanical storage (flywheels). Because of the commonality of underlying technologies, secondary batteries for electrochemical energy storage are addressed in Section 7.2. Capacitors for continuous use are critical components of power conditioning and are addressed in Section 7.4. Technologies for integrating capacitive stores into pulsed-power systems and converters/inverters are addressed in Section 7.1.

BACKGROUND

Energy storage devices are intended for pulsed applications that require short-term storage (microsecond-to-second) or long-term storage (several years). These devices can be charged and discharged in a pulsed or near-continuous manner. Examples of technologies used as energy storage include capacitors, inductors, and mechanical storage.

For mechanical storage, the energy is stored as in the form of angular momentum, such as that in a flywheel, which is used to drive a rotating generator or alternator.

For electrical storage, the energy is stored in the electric field of the dielectric medium (e.g., a capacitor) or in the magnetic field of the dielectric medium (e.g., an inductor). For chemical storage, the energy is stored in the reactants (e.g., batteries; see Section 7.2).

For pulsed-power applications, once energy is stored, it can then be extracted completely or incrementally. In the mechanical case, the flywheel storage device can be coupled to a switch or a switching network that, depending on the speed and other characteristics, can deliver pulses of power to some load. Some devices integrate the switching into the storage device and feed its pulsed output directly to the load. Once charging is complete, the switch is closed, and a pulse is delivered to the load. High-frequency inverters (DC-to-AC) can be used as a power supply to charge the storage device in a few milliseconds. Once charging is complete, a switch is closed, and pulsed power is delivered to some load.

In the high-energy case, mainly for weapons applications, systems of average powers in excess of 100 MW, for times of seconds to minutes, are integrated with pulsed-energy conditioning to create gigawatt-class repetitive pulses of energy from milliseconds down through submicroseconds, at voltages from several kilovolts up to megavolts.

Selected military applications (e.g., high-power radars, ECMs, and DEWs) may emerge and demand a class of precisely conditioned electric energy that has no direct foreseeable commercial or industrial application. However, for different applications, industry may be able to use the components used to produce these levels of output. High-energy electronics have limited commercial applications. Assured development, therefore, will require government sponsorship.

Peak power, pulse shape, pulse duration, repetition rates, firing rates, silent watch, and system energy storage recharging times represent militarily critical performance parameters that, in many cases, transcend known commercial, industrial, or consumer applications. In addition, high-energy electronics packaging currently requires parallel/series combinations of components in the power train to achieve reliability, fault tolerance, and graceful aging at performance levels greater than 10 times today's commercial standards. See Figure 7.3-1.

Power Conditioning
Continuous

	SOTA	3 YRS	5 YRS	10 YRS
Energy density (J/cc)	**1.0**	**3.0**	**4.0**	**6.0**
Specific energy (J/g)	**1.0**	**2.0**	**3.0**	**5.0**
Frequency kHz	**50**	**100**	**> 200**	**> 200**
Temperature ($_{j}$C)	**125**	**200**	**350**	**350**

Figure 7.3-1. DoD Capacitors' Technical Goals

Capacitors

Capacitors have wide applications in consumer electronics, telecommunications, computers, medical instruments, aircraft, spacecraft, robotics, and automobiles in the military and commercial sectors. These applications determine the performance of the capacitor market. For example, if a country has a strong consumer electronics sector in its economy (such as Japan), the capacitors found in those types of applications are going to perform particularly well. Most of the capacitors being manufactured are for small electronic devices, primarily consumer oriented. The economic forces affecting these devices are well known, and a wealth of market data is available.

The economic forces affecting the consumer market are quite different from those affecting the capacitors of interest to this analysis. Capacitors capable of very high energy density at very high power are a special subcategory, and little economic information is available since this is such a specialized market. However, certain comparisons can be made.

Capacitors, in general, are following the trend in semiconductor technologies: components are getting smaller, lighter, and more powerful. Greater amounts of capacitance are being fit into the same or smaller sized packages. These developments have compelled manufacturers to keep up with industry demands, and these demands have created pressure on the manufacturers to make huge capital expenditures on manufacturing equipment so they can produce state-of-the-art technology. This causes a market consolidation. Firms who cannot maintain these expenditures either fold, get bought out, or find a niche where they can remain solvent. Consolidation has occurred mostly in the capacitor market, and those firms who are present and functioning in the market will most likely continue be a factor in the future.

A conventional capacitor is an electrical circuit element having the ability to store an electrical charge. The current (i) passing through the element is proportional to the derivative of the voltage across it:

$$i = C\frac{dV}{dt} \quad . \tag{7.3-1}$$

Solving for the voltage and integrating yields

$$V = \frac{Q}{C} \quad , \tag{7.3-2}$$

where the proportionality constant C is the charge storing capacity of the element and is the Capacitance, with Q in units of coulombs and V in volts. The capacitance is thus measured in *farads.* A coulomb/volt is equal to one farad. One farad is a large amount of electrical capacitance but not uncommon in electrolytic or electrochemical form. The electronics community typically deals with capacitors of microfarad [i.e., μF (10^{-6} Farads)] size. Capacitance can be calculated directly if the voltage is known for a given charge. Capacitance charge or energy delivery is characterized by a voltage drop from a higher to lower potential (+ to –). Such a voltage drop indicates that energy is being removed from the capacitor and, for example, stored or dissipated. The power and stored energy for a capacitor may be calculated respectively from the following relationships:

$$p = Vi = CV\frac{dV}{dt} \quad \text{and} \tag{7.3-3}$$

$$w = \int pdt = \int CV\frac{dV}{dt}dt = \frac{1}{2}CV^2 \quad . \tag{7.3-4}$$

The parallel plate capacitor consists of two electrical conductor plates separated by a distance, d, in, for example, a vacuum. The electric field, E, between the plates of such a capacitor is the charge per unit area, σ, divided by the permittivity ε_o of free space for a capacitor in a vacuum.

$$E = \frac{\sigma}{\varepsilon_o} \quad , \tag{7.3-5}$$

where, ε_o=8.85^{-12} Farads/m.

The voltage in such a capacitor is equal to the electric field, E, multiplied by the distance, d, between the plates. The total charge, Q, on one plate of the capacitor is σ multiplied by the area, A, of the plate. Substituting yields the following relation for the parallel plate capacitance:

$$C = \varepsilon_r\varepsilon_0 A/d \quad , \tag{7.3-6}$$

where ε_r is the relative dielectric constant of the dielectric material separating the electrodes.

The voltage in such a capacitor is equal to the field, E, multiplied by the distance d between the plates. The total charge, Q, on one plate of the capacitor is σ multiplied by the area A of the plate. Substituting yields the following relation for the parallel plate capacitance:

The dielectric insulator between the capacitor plates is a key feature in high-density packaging of capacitors. Simultaneously, the capacitor must perform to demanding military parameters and be of a size and configuration to fit into relatively small and sometimes unusually shaped spaces in military systems. As seen in Eq. (7.3-6), as the thickness of the dielectric material decreases and the dielectric constant increases, the capacitive value, "C," will increase. The main concern with the dielectric thickness as it decreases is the void-free feature of the material to prevent voltage breakdown. This problem can be attacked in two ways: (1) developing a reliable manufacturing process that produces materials without imperfections of consequence and (2) having a self-healing dielectric material that will seal when experiencing initial voltage breakdown.

A wide range of possible dielectric materials exists: solid, liquid and gas.

Capacitive storage to meet military pulse-power needs requires a level of capacitance significantly larger than most commercial applications. Simultaneously, packing in military systems demands that the storage function is achieved in devices that are substantially smaller in volume than would be found in nonmilitary endeavors.

REFERENCES

E. Manna, *Energy Storage Overview,* ONR Advanced Electrical Power Systems Strategic Planning Program Review. October 5, 2000.

D. O'Brien, "Introduction to Capacitors," http://www.nacc-mallory.com/techa5.htm, June 1999.

LIST OF MCTL TECHNOLOGY DATA SHEETS
7.3. ENERGY STORAGE

MCTL DATA SHEET 7.3-1. CAPACITIVE STORAGE

Critical Technology Parameter(s)	**Electrostatic** Energy density > 2.5J/cc Loss factor < 0.001 High-temperature capabilities –55 to > 200 °C Repetition rate for pulsed 0.1 to > 100 pps Continuous operation 100 kHz and greater **Electrochemical** • Charge/discharge time of 1 to 300 sec • Energy density ~ 5 W-hrs/kg (inorganic electrolytes), 10 to 15 W-hrs/kg (organic electrolytes) • Power densities > 10 kW/kg.
Critical Materials	High-performance materials; metals; packaging.
Unique Test, Production, Inspection Equipment	Production methods for capacitive storage devices are well known. Testing of these devices can be accomplished with relatively simple equipment.
Unique Software	None identified.
Major Commercial Applications	HEVs; automotive ignition systems; portable electronics; computers; telecommunications; remotely controlled actuators; emergency back-up power supplies; arc welding; oil/well drilling; rock splitting; medical defibrillators; high-power flash lamps; motor start circuits; utilities; aerospace; and so forth.
Affordability Issues	Cost is one factor limiting the widespread use of high-performance capacitors. Because of cost, material development is expensive and difficult to mature and transition. The high-voltage, pulse-power capacitor technology will remain largely for military applications; however, cost can be reduced, as other applications in the market become known.
Export Control References	WA ML 11;[24] WA Cat 3; USML XI, CCL Cat 3.

BACKGROUND

Electrochemical: Recent advances in materials and design have resulted in significant improvements in capacitive storage for power and for energy density. CDL capacitors have emerged as a viable technology for back-up power and for EVs. These capacitors deliver power effectively in the 1-to-10-second time regime. In terms of performance (energy storage and power), CDLs fall between batteries and conventional electrostatic capacitors. One of the recurring themes at the system level is the combination of batteries and capacitors, which takes advantage of the energy density of batteries and the power density of capacitors to meet repetitive high-power-drain applications (such as starting and power surge capabilities in hybrid vehicles).

REFERENCES

Andreas A. Neuber, *Pulsed Power Tutorial. Pulsed Power Workshop,* SAE Power Systems Conference, San Diego, CA, October 2000.

[24] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.3-2. AC CAPACITORS

Critical Technology Parameter(s)	**Continuous** Energy density 2.5 (J/g) Dissipation factor (loss) 0.005 and good clearability (self-healing) of the dielectric Improved temperature capability >125 °C
Critical Materials	Novel polymers; parylenes; ceramics; diamond-like carbon (DLC); nitrides; glass-ceramic composites; ceramic-polymer composites; polymer-polymer composites; light-weight packaging materials.
Unique Test, Production, Inspection Equipment	Production methods for these devices are well known. Testing of these devices can be accomplished with relatively simple equipment. Test procedures borrowed from traditional capacitor and battery-testing methods can be used.
Unique Software	None identified.
Major Commercial Applications	EVs; motor start circuits; aerospace; power conditioning; filtering; inverters, and so forth.
Affordability Issues	The high-voltage, pulse-power capacitor technology will remain largely for military applications; however, cost can be reduced as other applications in the market become known.
Export Control References	WA ML 11;[25] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

AC capacitors are used basically in three areas: high frequency power conditioning, high voltage 60-Hz power factor correction, and 60-Hz applications for commercial products such as lighting ballast and motor applications for start and run conditions.

[25] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.3-3. ELECTROCHEMICAL CAPACITORS

Critical Technology Parameter(s)	• Discharge time of 1 to 300 sec • Charge time of 1 to 300 sec • Energy density ~ 5 W-hrs/kg (inorganic electrolytes), 10 to 15 W-hrs/kg (organic electrolytes) • Power densities > 10 kW/kg • Charge/discharge efficiencies ~ 80% at high rates and 98% at low rates • Cycle life >100,000 cycles at 100% DOD • Charge and discharge current densities > 100 A/cm^2 • Temperature range –55 to +85 °C, 98%-plus reliability.
Critical Materials	Improved organic and inorganic electrolytes with higher breakdown voltages; improved microporous polymeric separators; improved active carbon materials with extremely large active surface areas (over 3,000 m^2/g) (e.g., carbon nanotubes and glassy carbon fibers). Electrode materials and electrolyte. Must perfect packaging process along with materials development.
Unique Test, Production, Inspection Equipment	CY91 R/T: Electrochemical capacitors scaling verified to > 100-kJ levels: • R: intrinsic break down laminates, impregnants, and model sections • T: continuous: > 30 J/Kg; 20 kHz; > $l0^8$ cycles; 2 F; 1.5 kV; inverter.
Unique Software	None identified.
Major Commercial Applications	Advancements in power and/or energy density will enable more widespread use. Electrochemical capacitors will be used as a battery load leveler and a battery replacement (motor drive bus ride-through, UPS, portable electronics, automotive electronics). Presently used for memory backup. HEVs; automotive ignition systems; portable electronics; computers, telecommunications; avionics; remotely controlled actuators; emergency back-up power supplies. **Note:** *To date, very few CDL products are on the marketplace.*
Affordability Issues	Cost is one limiting factor in the widespread use of these capacitors. Cost must come down to make these devices a viable commercial product. Current cost for Japanese capacitors is about $0.25/F.
Export Control References	WA ML 11;[26] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Electrochemical devices that are produced in modular units and are scalable in size for meeting power load requirements are designed for HEVs. They are most likely serially assembled in banks of capacitors to meet selected power loads. They are produced mostly in cylindrical configurations out of materials that provide very large active surface areas for the electrode/electrolyte interface to support the generation and storage of ions along the surface.

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26 Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.3-4. HIGH-REPETITION-RATE/CONTINUOUS CAPACITORS

Critical Technology Parameter(s)	Energy density ≥ 2.5 (J/g) Dissipation factor (loss) ≥ 0.001 Operating temperature range ≥ –55 to > 150 °C High frequency > 50 kHz
Critical Materials	Novel polymers; ceramics; DLC; nitrides; glass-ceramic composites; ceramic-polymer composites; polymer-polymer composites; impregnants; lightweight packaging materials.
Unique Test, Production, Inspection Equipment	Production methods for these devices are well known. Testing of these devices can be accomplished with relatively simple equipment. Test procedures from traditional capacitor testing methods can be used. Precision winding machines also critical to fabricating superior capacitor devices.
Unique Software	None identified.
Major Commercial Applications	Motor start circuits; aerospace; power conditioning; filtering; inverters/converters; power factor correction ballasts; and so forth.
Affordability Issues	New dielectric materials are expensive, and cost issues affect affordability and acceptance into market.
Export Control References	WA ML11;[27] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

The high-repetition-rate/continuous capacitors are used in inverter circuits and usually stores and transfers a great deal of energy, and it does it continuously—not in bursts. It is obvious that an extremely low dissipation factor will be necessary for this type of device to function well.

[27] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.3-5. FLYWHEELS

Critical Technology Parameter(s)	System-level specific energy (> 50 W-hrs/kg); specific power (> 1,000 W/Kg); life [> 20 years in low earth orbit (LEO) or >100,000 cycles].
Critical Materials	High strength-to-weight ratio materials (composites) for energy storage rotor; high-temperature superconducting materials for low-drag passive magnetic bearings; techniques for high energy-rate/high peak-power extraction; magnetic (and other) bearing technologies for long storage life and efficient operation; materials such as Kevlar, Metglass, and graphite epoxy.
Unique Test, Production, Inspection Equipment	Flywheels are typically high-energy devices that require a high-vacuum spin pit for operational testing. Fabrication of the flywheel typically requires precisely controlled filament winding machinery (if it is a spun composite wheel).
Unique Software	Active magnetic bearings are often used for flywheel suspension. The control logic is typically custom designed and implemented on a digital signal processor board. Specialized analysis codes, often proprietary, are used for analysis of flywheel stresses and system dynamics. Motor/generators provide the electrical interface for the flywheel system and require unique control methods to incorporate both modes of operation. Also, voltage-regulation control software is often used to take advantage of the flywheel's ability to operate without a separate charge control module.
Major Commercial Applications	UPSs; utility-level energy storage; LEO satellites; electric transit vehicles (i.e., bus and train); rock splitting (fracturing) arc (few tons per hour).
Affordability Issues	None identified.
Export Control References	None identified.

BACKGROUND

A flywheel is an energy storage system. As such, its performance is defined by the following parameters:

- Total specific energy (based upon maximum rotational speed)
  - The ultimate speed relates directly to ultimate stress, and the stress limit for a flywheel is usually expressed in tip speed. Thus, saying that the specific energy is based on the maximum rotational speed is essentially correct, although one would need more information to calculate specific energy.
- Usable specific energy ("DOD," from maximum/minimum speed ratio)
- Specific power
- Life (i.e., number of cycles to failure)
- Coefficient of friction (i.e., drag) caused by idling losses in support system.

  System Eff → Round trip Eff : want to retrieve W/hrs 90 to 92 percent [E_out/E_in – measured @ terminals].
  Operating Temp → Temp Swing : 70 to 100 °C

Service life (cycles): 50,000 (design). Plan to put one on the Space Station, designed for life of station (15 yrs). Five-year life, each with two servicings (batteries).

The specific energy of a system is application specific. For example, rotor specific energy (comparable to battery cell) 44 W-hrs/kg (2005), 2010 projections up to 66 W-hrs/kg (by NASA). Some of today's rotors have 90 W hrs/kg (that corresponds to around 40 W-hrs/lb]. Further gains will come at the system level (magnetic bearing, control)—20 W-hrs/kg currently (Texas A&M, NASA work).

Since flywheels are spinning bodies, an additional parameter that defines acceptable vibration levels (allowable spectrum at bearing mounts) imparted to the host platform should be considered. Further, a key parameter is tip-speed, the product of angular velocity and radius. Research objectives include high specific energy and high energy-rate (power) (specific power) extraction for a variety of high-energy applications, such as DEW and HEVs.

Flywheel storage has been under development for many years. For mobile platforms, the momentum present in a flywheel presents an interesting challenge for the agility of the host vehicle in which it is installed. The bearings upon which the flywheel is mounted are subjected to significant stress (which can be easily mitigated using gimbal mounts) when torque is induced through a change in vehicle direction.

Flywheels generally come in two types (metallic and composite) based upon the materials from which they are constructed. The Russians have led in the development of metallic (titanium) flywheels. The United States has chosen to develop composite flywheels, using multi-ring, press-fit rotors (the most common) that do not "disintegrate." The first failure mode for this type of design is outer ring delamination.

By contrast with traditional flywheels, which were large-diameter, high-mass configurations, the advances in structural materials (and specifically composites) allow the designer to increase the speed of rotation. Since the energy stored scales directly with the mass and as the square of the angular velocity, this design approach allows higher specific energies. Further, the general consensus appears to be that the failure mechanism for the composite materials (delamination) offers substantial safety benefits.

REFERENCES

I.R. McNab, "Developments in Pulsed Power Technology," *IEEE Trans. Magn.,* Vol. 37, No. 1, January 2001. pp. 375–378.

SECTION 7.4—POWER CONDITIONING, CONTROL, AND DISTRIBUTION

Highlights

- Power conditioning is an important process involved in modifying the source output to have the characteristics required by the load.
- Voltage, current, pulse shape, and frequency are the electrical parameters affected by power conditioning.
- Unique loads require power to be delivered in specifically shaped continuous or pulsed waveforms.
- Advanced weapons of precision and wide-area mass destruction, radar, countermeasures, and communications systems will be enabled through next-generation-plus, high-energy electronics systems, including the prime energy sources.

OVERVIEW

Power conditioning is the process involved in modifying the source output to meet the desired load conditions. Such loads can include military and commercial applications. Military applications range from charging a battery, to forming pulses for a weapon subsystem, to electric motor drives. Two types of conditioning are defined by the amount of time over which power is supplied: continuous duty and pulsed or burst mode. Continuous duty is defined as power supplied to a load continuously, which implies bursts lasting longer than 1 sec (since semiconductor devices reach their thermal equilibrium in less than 1 sec). Bursts lasting less than several seconds are considered pulsed power and generally have higher average powers. Pulsed-power conditioning discharges a high-energy storage bank in a low repetition-rated burst mode. For some applications, long pulses that last from several microseconds to seconds may be fed into a fast-conditioning stage, which creates bursts with high power lasting for much shorter durations.

BACKGROUND

Power conditioning, control, and distribution systems comprise a wide range of critical component and subsystem integration and packaging technologies. Key design considerations include safety and reliability, mission requirements, size, weight, and thermal management. In many cases several different power conditioning steps are required. For example, AC voltages may be stepped-up for transmission over distances to reduce resistive losses and stepped down at the point of use for safety reasons, with different voltage and current (power) levels being delivered for different functions. While some electric motors can be run directly with AC power, other motors and most electronic systems, ranging from hand-held calculators to the largest communications systems, require DC, or pulsed power—in effect, a pulse of DC delivered with specified voltage, current, and time characteristics.

Component design and integration technologies are critical to meeting system packaging constraints. Figure 7.4-1, adapted from a slide provided by the U.S. Air Force, shows some of the significant contributors to the size and weight of a nominal power conditioning and control subsystem.

The following discussion focuses on the technical issues associated with militarily critical components.

Capacitors

Capacitors have wide applications in consumer electronics, telecommunications, computers, medical instruments, aircraft, spacecraft, robotics, inertial confinement fusion, nuclear effects simulation, Equation of State (EOS) physics research, and vehicles in the defense and commercial sectors. These applications determine the performance of the capacitor market. For example, if a country has a strong consumer electronics sector in its economy

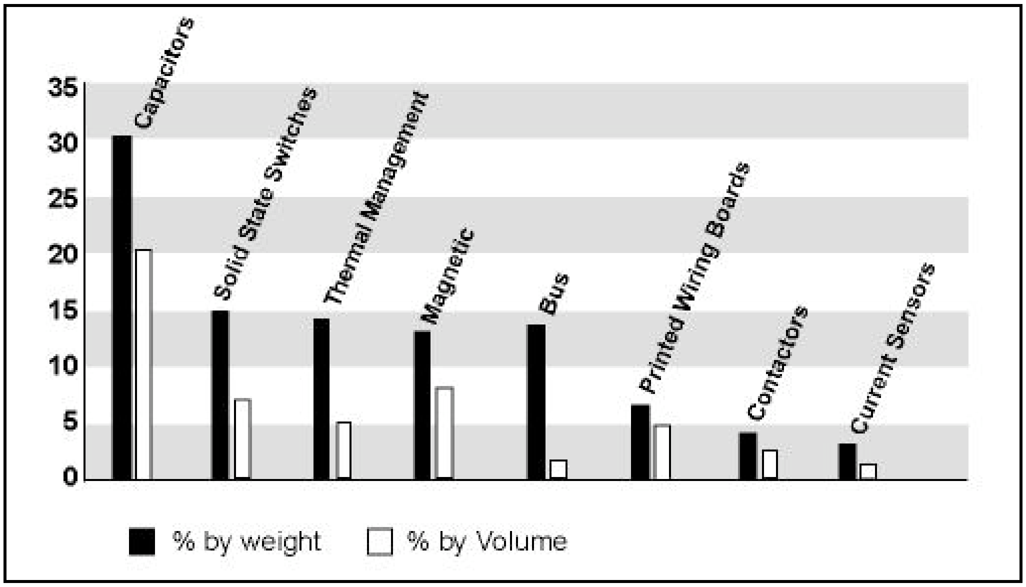

Figure 7.4-1. Typical Breakout of Power Conditioning Components by Contribution to Size and Weight of the Complete Subsystem

(e.g., Japan), the capacitors found in those types of applications are going to perform particularly well. Most of the capacitors being manufactured are for small electronic devices, primarily consumer oriented. The economic forces affecting these devices are well known, and a wealth of market data is available.

The economic forces affecting the consumer market are quite different from those affecting the capacitors of interest to this analysis. Capacitors capable of very high energy density at very high power are a special subcategory, and little economic information is available since this is such a specialized market. However, certain comparisons can be made. Capacitors, in general, are following the trend in semiconductor technologies: components are getting smaller, lighter, and more powerful. Greater amounts of capacitance are being fit into the same or smaller sized packages. These developments have compelled manufacturers to keep up with industry demands, and these demands have created pressure on the manufacturers to make huge capital expenditures on manufacturing equipment so they can produce state-of-the-art technology. This causes a market consolidation. Firms who cannot maintain these expenditures either fold, get bought out, or find a niche where they can remain solvent. Consolidation has occurred mostly in the capacitor market, and those firms who are present and functioning in the market will most likely continue be a factor in the future.

Switches

Switches are *critical* components for high-power conditioning and pulse formation. They are mainly used in networks designed to convert power from one form to another. A switch's internal environment can be solid state, gas, magnetic, or liquid. The driving requirements in switch technology are high efficiency (greater than 98 percent), negligible internal inductance (much less than 1 nH/A), and increased operating temperatures (–55 through +500 °C desirable). The latter is being realized through SiC switches, which are an emerging approach to the temperature problem. Applications are motor control systems, UPSs, power conditioning, high-voltage DC transmission, inductive heating, and many other commercial applications. Figure 7.4-2 compares voltages and speeds for various switches, and Figure 7.4-3 highlights the trends for several switches.

In establishing the operating parameters of high-energy switches, care must be taken to avoid subjecting the device to conditions that are potentially capable of causing a fault. For the SCR switch, a fault is a catastrophic event. The spark gap and the triggered vacuum switch, however, regain most, if not all, of their capabilities after a fault. A fault can also cause damage to the overall system as well as the loss of the effectiveness of the shot or the shot itself.

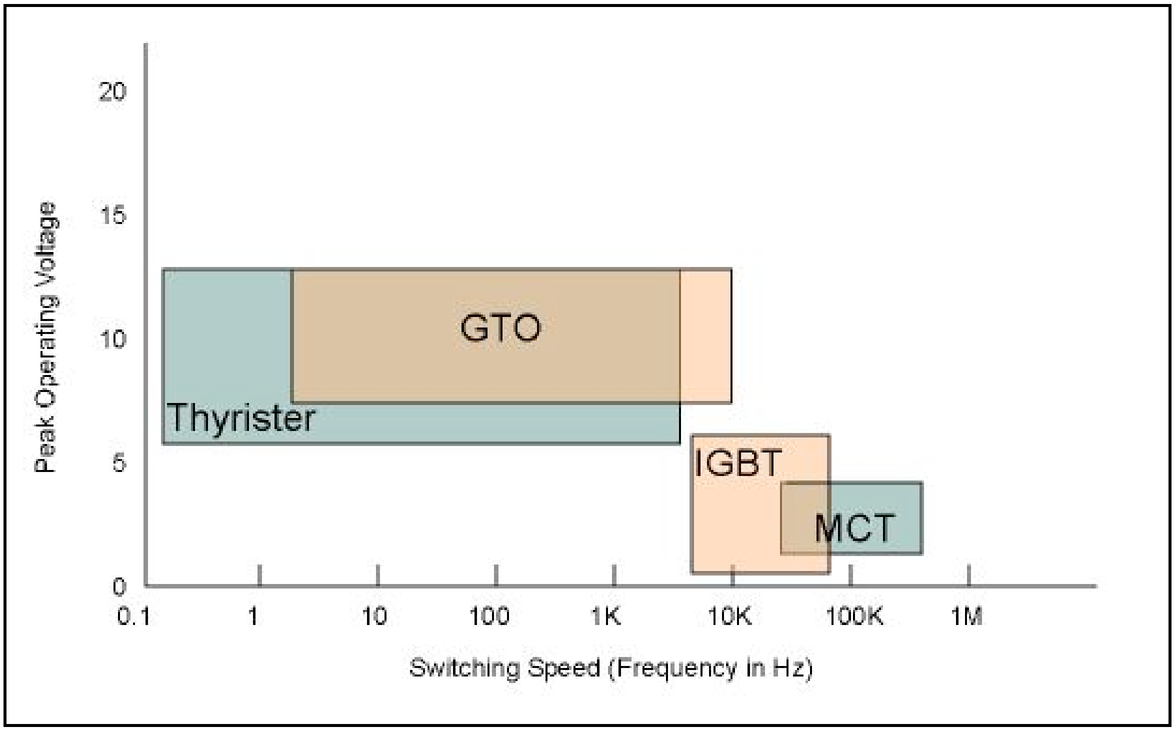

Figure 7.4-2. Speeds for Switching Devices (Source: ATAR)

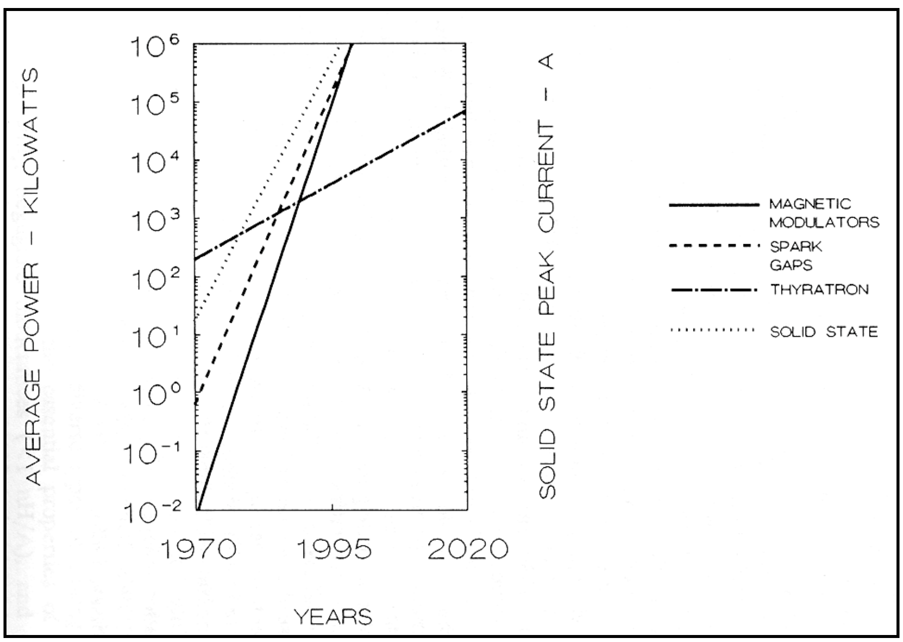

Figure 7.4-3. Trends for Switching Technology

LIST OF MCTL TECHNOLOGY DATA SHEETS
7.4. POWER CONDITIONING, CONTROL, AND DISTRIBUTION

MCTL DATA SHEET 7.4-1. DIELECTRICS FOR PULSE-POWER CAPACITORS

Critical Technology Parameter(s)	***In order of priority***: Voltage breakdown strength > 20 kV/mil Dissipation factor (loss) 0.0005 (% @ 25 ºC, 1 kHz) Self-healing properties Dielectric constant > 3.0 (K)
Critical Materials	Novel polymers; parylenes; ceramics; DLC; nitrides; glass-ceramic composites; ceramic-polymer composites; polymer-polymer composites; impregnants.
Unique Test, Production, Inspection Equipment	Semiconductor-grade material deposition equipment and processes (i.e., vacuum deposition methods). Precision winding machines also critical for fabricating superior capacitor devices.
Unique Software	None identified.
Major Commercial Applications	Arc welding; oil/well drilling; rock splitting; medical defibrillators; high-power flash lamps.
Affordability Issues	The high-voltage, pulse-power capacitor technology will remain largely for military applications; however, cost can be reduced as other applications in the market become known. A major concern is a reliable source of supply for specialty dielectrics needed for high energy-density capacitors since they are required sporadically and in low volumes.
Export Control References	WA ML 11;[28] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

There is an unquestionable need for high energy-density capacitors for a variety of military and commercial applications. Polymeric materials have the advantage because they can be made in thin sheets at reasonable costs. At the present time, biaxially oriented polypropylene (BOPP) is the material of choice for high energy-density capacitors. The only drawback of this material is its relatively low-use temperature of 90 to 100 ºC. The current BOPP materials are made from isotactic polypropylene, which is rendered biaxially oriented during blown film extrusion or by tentering after horizontal film extrusion. The best quality BOPP in thin-film form made specifically for capacitors exhibits a dielectric strength on the order of 800 V/μm.

Presently, AFRL has started the commercialization process of DLC dielectric film, which can achieve dielectric strengths approaching 900 V/μm to 1 k V/μm (laboratory prepared samples) and perhaps even greater. The question now facing researchers is, What polymeric film could be made that would result in a substantial improvement in the dielectric strength of DLC or BOPP? At some high level of voltage stress, any organic polymer will suffer breakdown, followed by catastrophic failure. The literature is filled with hundreds of articles that present several different mechanisms by which breakdown of polymers occur because of an impression of high voltages. Regardless of the mechanism, the conclusions that pertain to the possibility of developing a polymeric film of a dramatically high dielectric strength are one and the same. It is widely accepted that the breakdown of a polymeric insulator occurs by an electro-thermal mechanism. (See Table 7.4-1.)

[28] Including associated software and technology specified in WA ML 18, 21, and 22.

Table 7.4-1. Overview of Available and Upcoming Dielectrics

Material	Dielectric Constant (K)	Specific Gravity (g/cm^3)	Breakdown Strength (kV dc/mil)	Dissipation Factor (% @ 25 °C, 1 kHz)	Max Operating Temperature (°C)	Energy Density of the Dielectric Material (J/cc) 1
Polycarbonate	2.8	1.20	4.5	0.12	125	0.39
Polypropylene	2.2	0.92	14.5	0.01	105	3.17
Polyester	3.3	1.40	13.0	1.00	85	3.83
Polyvinylidene difluoride	10.0	1.80	10.0	1.50	125	6.86
Polyphenylene sulfide	3.0	1.35	9.0	0.06	200	1.67
Teflon	2.1	2.20	7.4	0.05	200	0.79
FPE	3.3	1.22	13.0	0.03	275	3.83
DLC	3.5	1.80	20.0	0.05	> 250	9.60
Lithium Power Technology (Experimental Zafilm)	5.0–7.0	0.95–1.80	15.0–22.5	< 0.01	150–175	7.72–24.3

Note 1 for Table 7.4-1: *Not completed assemblies.*

REFERENCES

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Hengkum Xie Xinyan et al., "The Energy Criterion for Breaking Chemical Bonds in Electrical Breakdown Process of Polymers," *Proceedings of the 4th International Conference on Properties and Applications of Dielectric Materials*, July 3–8, 1994, Brisbane, Australia.

Steven Boggs and Jimbo Kuang, "High Field Effects in Solid Dielectrics," *IEEE Electrical Insulation Magazine*, Vol. 14, No. 6, 1998, pp. 5–12.

George G. Malliaras et al., "Nondispersive Electron Transport in Alq_3," *Applied Physics Letters*, Vol. 79, No. 16, 2001, pp. 2582–2584.

MCTL DATA SHEET 7.4-2. LOW-REPETITION-RATE OR BURST CAPACITORS

Critical Technology Parameter(s)	Energy density 2.5 (J/cc) Low dissipation factor < 0.005 (% @ 25 ºC, 1 kHz) Number of shots (nominal) 10^5 Pulse repetition rate 0.1 to 10 (Hz) Discharge efficiency > 85% Low repetition rate is approximately 0.1 to 10 pulses per second, < 5 percent duty cycle, 50 kJ; 20 kV.
Critical Materials	Novel polymers; parylenes; ceramics; DLC; nitrides; glass-ceramic composites; ceramic-polymer composites; polymer-polymer composites; impregnants; lightweight packaging materials.
Unique Test, Production, Inspection Equipment	Production methods for these devices are well known. Testing of these devices can be accomplished with relatively simple equipment. Test procedures borrowed from traditional capacitor and battery testing methods can be used. Precision winding machines are critical for fabricating superior capacitor devices.
Unique Software	None identified.
Major Commercial Applications	DEWs [laser, radar, radio frequency (RF), microwave, CPB]; EM and electrothermal (ET) launchers; electronic countermeasures/jammers; electromagnetic armor/active protection system; and mine clearing.
Affordability Issues	The high-voltage, pulse-power capacitor technology will remain largely for military applications; however, cost can be reduced as other applications in the market become known.
Export Control References	WA ML 11;[29] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

A need for large amounts of electrical power in several DoD military systems has been envisioned for some time. A technical barrier that has impeded the development of such systems has been the required volume and weight of the power conditioning subsystem. Capacitors account for the largest portion of weight and volume within the system. The size and weight of capacitors generally increase as the amount of energy they can store increases. As power and energy requirements increase in military systems, the size and weight of the capacitors used will also increase. Therefore, the essential problem is to increase the amount of energy that can be stored by a given volume or weight of the dielectric. This is accomplished by developing materials of higher quality and with better electrical and thermal properties than those currently available. Improvements in packaging will also assist in obtaining more energy-efficient capacitor devices with lower ESR and ESL. A lower value of ESR and ESL means better efficiency during the energy transfer from the capacitor to the load.

State-of-the-art, high-performance capacitor dielectrics, impregnants, foils, conductors, and/or advanced packaging concepts have to be developed to enable leading edge, pulsed-power, high energy-density capability with nanosecond delivery rates. To date, biaxially oriented polypropylene is still the best dielectric material for the high-voltage, pulse-power capacitor market because of its high voltage breakdown strength and low dissipation factor. It has excellent clearing capabilities and is readily available. This material has the capability to increase the energy-density capability to 1.5 to 2.0 J/cc, from the current state of the art of 1.0 J/cc.

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[29] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.4-3. MEDIUM-REPETITION-RATE CAPACITORS

Critical Technology Parameter(s)	Energy density ≥ 2.5 (J/cc) Low dissipation factor 0.005 (% @ 25 ºC, 1 kHz) Pulse rate > 10 pps
Critical Materials	Novel polymers; DLC; polymer-polymer composites; impregnants; lightweight packaging materials.
Unique Test, Production, Inspection Equipment	Production methods for these devices are well known. Testing of these devices can be accomplished with relatively simple equipment. Test procedures borrowed from traditional capacitor and battery testing methods can be used. Precision winding machines are critical for fabricating superior capacitor devices.
Unique Software	None identified.
Major Commercial Applications	EW; communications; laser radar.
Affordability Issues	High-voltage, pulse-power capacitor technology will remain largely for military applications; however, cost can be reduced as other applications in the market become known.
Export Control References	WA ML 11;[30] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

For medium-repetition-rate capacitors, the general research objectives are higher energy density, a lower dissipation factor, lower internal resistance, higher temperature operation, and graceful degradation. In applications where high peak currents and voltages are needed, foil capacitors are usually, required and benefits from self-healing technology cannot be used. (Self-healing technology allows operation very near the breakdown field of the film.) These medium-repetition-rate devices can also experience significant root mean square (rms) currents, giving way to hot-spot temperature rises and thermal runaway.

[30] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.4-4. ULTRAVIOLET DRIVEN INSULATING DIAMOND SWITCHES (UV DIDSs)

Critical Technology Parameter(s)	Peak power ≥ 50 mW I_{peak} ≥ 1 kA V_{peak} ≥ 100 kV Peak current density > 10 kA/cm^2 di/dt 10 kA/μs to 10^3 kA/μs (UV-driver limited) Rise/fall times 1 ns to 50 ns (UV-driver limited) Duty cycle (application dependent) 10^{-2} to 10^{-5} Efficiency $> 75\%$
Critical Materials	Highly insulating, high thermal conductivity, synthetic or natural diamond; high-temperature contacts and leads because of the intrinsic energy dissipation inherent in switches. This would suggest materials that have high specific heat and high conductivity. High breakdown strength, high thermal conductivity, UV transmitting packaging materials to reduce surface flashover.
Unique Test, Production, Inspection Equipment	Equipment that can fabricate a system of switches that provides the required synchronism better than 1 ns for parallel operation.
Unique Software	Software that can support the fabrication process.
Major Commercial Applications	So far, the only applications for this technology have been military. Potential commercial opportunities include power transmission on the grid, high-speed rail traction and UPSs for the semiconductor and the automotive industries.
Affordability Issues	Too early to establish. May or may not be a big issue depending on the availability of synthetic diamond of sufficient quality with which to fabricate switch.
Export Control References	WA ML 11;[31] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Diamond has unique properties—particularly its thermal characteristics, which include greater temperature resistance (except in oxidizing environments) and extremely high thermal conductivity (25 W/cm K)—that make it highly attractive for uses in high-power, pulsed switch applications. Diamond has high electrical breakdown strength (~ 10 MV/cm), which allows for high-voltage switches in small packages.

Diamond is a WB material (5.5 eV), and this large bandgap results in reduced leakage of currents. Undoped, dielectric-quality diamond switches from its normal insulating state to a conducting state by electron beam injection, which generates electron-hole pairs, or by UV photoconductivity and permits bipolar conduction. Conduction ceases when incident radiation is removed. Hence, diamond demonstrates fast turn-on/turn-off repetition rates. In the conducting state, resistance can be less than 1 ohm. Also, UV DIDS may be inherently less susceptible to damage from radiation weapons effects.

Using diamond as a semiconductor in switches is also attractive, but this technology is still in early development because of the limitations of synthetic diamond quality. Efficient semiconducting devices have not been made using polycrystalline diamond. To date, single crystal diamond must be grown homoepitaxially and has defect densities that are still quite high, not to mention the lack of a shallow n-type dopant.

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31 Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.4-5. HIGH-PRESSURE LIQUID DIELECTRIC SWITCHES

Critical Technology Parameter(s)	I_{peak} ≥ 50 kA V_{peak} ≥ 250 kV di/dt ≥ 10^3 kA/s Risetime ≥ 50 ns Repetition rate 50 to 150 pps Lifetime > 10^7 pulses
Critical Materials	High-strength, lightweight materials for switch casing and electrodes; high breakdown strength oils whose breakdown voltage increases with pressure (chemical formulation is unchanged because of breakdown and whose only solid by-product is carbon).
Unique Test, Production, Inspection Equipment	Diagnostic equipment to ensure switch performance; high-speed cameras; compact, high-pressure pumping station capable of clearing switch in times commensurate with 50-to 150-Hz operation.
Unique Software	Electric field modeling and diagnostic programs for switch optimization and quality control.
Major Commercial Applications	Limited applications in particle accelerators. Pulsed-power requirements will be unique to specific military systems.
Affordability Issues	Switches custom made to requirements for specific military systems.
Export Control References	WA ML 11;[32] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

The development of pulse power for NWE simulation, inertial confinement fusion, particle beam weapons, and HPM has shown a steady evolution in high-voltage switch technology. Mobile, high pulse-repetition rate modulators for HPM systems are required to be small, low weight, and rugged and to be able to operate in adverse environments. Oil dielectric developments have demonstrated MV-level operation, reliable, reproducible, multichannel, low-jitter switching of large currents for use in intermediate impedance pulsers. However, clearing-time issues for operation at 50 to 150 Hz require substantial oil flow systems. The high-pressure liquid dielectric switch capitalizes on previous triggered oil-switch technology but adds high-pressure (greater than 1,000 psi) flowing oil that, because of the auxiliary components (primarily the compact, high pressure pump), localizes streamer channels and increases the electrical breakdown strength of the oil with only a modest penalty in size and weight.

[32] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.4-6. POWER SEMICONDUCTORS

Critical Technology Parameter(s)	Rate of turn current di/dt > 5,000 A/ns Voltage > 3,500 V Single wafer current @ 2 kHz switching > 1,000 A Single wafer device area > 70 mm Multichip module current @ 13-kHz switching > 150 A
Critical Materials	High purity float zone Si; Thin-Pak technology; flexible interconnect.
Unique Test, Production, Inspection Equipment	Surface-mount technology; electro-deposition processes; large-volume expitaxial reactors; large-volume substrate production facilities.
Unique Software	None identified.
Major Commercial Applications	Power quality devices, Flexible AC Transmission Systems (FACTS); commercial marine propulsion; battery energy storage; UPSs; hybrid cars; fuel-cell converters; wind power generation; traction drives for trains; industrial drives for manufacture and automation; EM launch; radar power supplies; sonar amplifiers.
Affordability Issues	Commercial applications are essential to support on-shore production.
Export Control References	WA ML 11;[33] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Power Switching Devices

Basically, power semiconductor devices consist of a variety of diodes, transistors, and thyristors. The diodes are a family of two-layer devices, the transistors are a family of three-layer devices, and the thyristors are a family of four-layer devices.

Power Diodes

Power diodes simply conduct in one direction and block in the other. Diode-based rectifiers are commonly used for AC/DC converters for feeding the propulsion inverter. In voltage-sourced converters, diodes are needed for reverse conduction. After forward conduction, the initial application of reverse voltage results in reverse surge current for short duration. In voltage-sourced converters, this reverse diode current is important because of its high impact on the required turn-on-current capability and losses of the main devices. Improvements in diode technology for reverse recovery current would have a significant impact on the cost of converters. Future development will spur the use of SiC diodes with negligible reverse/recovery current—even at the significantly higher cost of these diodes.

Transistor (IGBT)

A transistor conducts in the forward direction with a gate signal and turns off when the gate signal is removed. Transistors have a controlled turn-on. When the signal is less than what is needed for full turn-on, it will conduct while still holding partial anode-to-cathode voltage. This current-limiting feature is an important plus for transistors in buying time of a few microseconds—enough for protection purposes.

One type of transistor known as the IGBT has replaced GTO (a thyristor device) in a wide range of low- and medium-power applications up to several megawatts and even competing up to a few hundred megawatts. IGBTs are

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[33] Including associated software and technology specified in WA ML 18, 21, and 22.

highly integrated devices, with an MOS gate that is closely integrated with the cathode in a fine geometry of a few microns. This integration of an MOS gate results in a requirement of a few-volts gate signal for turn-on and turn-off. Thus, it has fast-switching capability and controlled di/dt during turn-on. These are major advantages for small- to medium-size converters and even high-power converters.

IGBTs, because of their highly integrated structure, are made in small sizes (1 to 2 cm^2) on large wafers. As a preferred approach for converter power up to a few megawatts, IGBTs and power diodes are packaged in a module so that functional insulation between the power electronics and the heat sink can be integrated. This module technology typically allows only single-sided cooling, which limits the heat transfer. At powers above a few megawatts, the more costly press-pack technology is preferred to exclude open circuit failures and to allow series connection with redundancy concepts.

IGBT technology is clearly preferred in lower voltage applications (up to 800 V). At higher voltage levels, the tradeoffs of the IGBT technology (in terms of lower voltage rating and higher on-state conduction losses) compared with thyristors (GTOs) generally necessitate a series connection of IGBTs or multilevel VSC converter topology to achieve even a 5-kV DC converter voltage rating and results in higher converter losses.

Thyristors

With a turn-on gate pulse, a thyristor latches into full conduction with a low-voltage drop in its forward direction and will not turn off with removal of the gate pulse. Turn-off requires a negative gate pulse. Conventional thyristors, used in line-commutated converters and cyclo-converters, are designed without their own turn-off capability. In this case, the thyristor recovers from its latched conducting state to a nonconducting state only when the current is brought to zero by other means. This approach leads to a highly efficient, highly rated device; however, these converters have a lagging power factor and high harmonics and are not very suitable for propulsion drive during low torque.

Several versions of thyristors with turn-off capability exist, some of which are relevant to the high-power converters.

GTO Thyristor

Like a conventional thyristor with a turn-on pulse, GTO turns-on in a fully conducting mode (latched mode) with a low forward voltage drop and turns-off when a turn-off pulse is applied to the gate in reverse direction. GTO has been used widely for many high-power applications. Because of its bulky gate drivers, high switching losses, and costly required snubbers, it has been used for non-PWM converters; however, in the future, it will be replaced by IGBTs or more advanced GTO-like devices.

Integrated Gate Commutated Thyristor (IGCT)

IGCT is basically a GTO with hard turn-off. This hard turn-off is achieved by minimizing the inductance between the gate and cathode, which, in combination with other advances in the packaging and gate drive circuit, achieves a fast turn-off and lower turn-off switching losses compared with a GTO. These devices have been introduced commercially and have the potential for propulsion drives and other large PWM converter applications.

IGCT is an example of the part-way integration of a gate drive circuit with the device itself (hence, its superior performance compared with GTO). With the advantage of lower on-state losses and snubberless converter application, IGCT has become a worthy competitor to IGBT for applications of 10 MW and above. However, IGCT does have a high gate-power requirement and is suitable for PWM frequencies up to 2 kHz.

Advanced Turn-Off Thyristors

An MOS Turn-off Thyristor (MTO) uses transistors to bypass the gate-cathode to assist in turn-off. Compared with IGCT, it has a smaller gate drive and fewer gate drive losses and achieves faster turn-off with lower turn-off switching losses. The MTO is an example of the further integration of the gate drive with the device. Although the MTO has not been introduced commercially, it has the potential for use in the medium-to-high power applications.

The Emitter Turn-Off Thyristor (ETO) is another variation of the GTO. It incorporates a low-voltage transistor (a MOSFET) in series with a high-voltage GTO and another MOSFET to bypass gate-cathode. This device has even faster turn-off and lower turn-off switching losses. This device is in the research stage and has not been introduced commercially.

Super GTO (SGTO) is another GTO device. Similar to an IGBT, it has a highly integrated gate-cathode structure. Also, like an IGBT, it is made in small sizes (1 to 2 cm^2) on large wafers. For high power, several SGTOs are housed in a bonded Si package. They have low forward conduction losses and fast switching characteristics. These devices are being introduced commercially in low-voltage transfer switches and have the potential for high power ratings in the future.

Solidtrons are voltage- or current-controlled turn-on devices based on MCTs and SGTOs. Solidtrons replace tubes and spark gaps for trigger and pulsed applications. These devices have extremely fast turn-on characteristics. The MCT version is replacing vacuum tubes and spark gaps for trigger applications in smart munitions. The SGTO version is being used in commercial nail guns and other pulsed applications.

Building Blocks

Figure 7.4-7 presents pictures of power semiconductor device components.

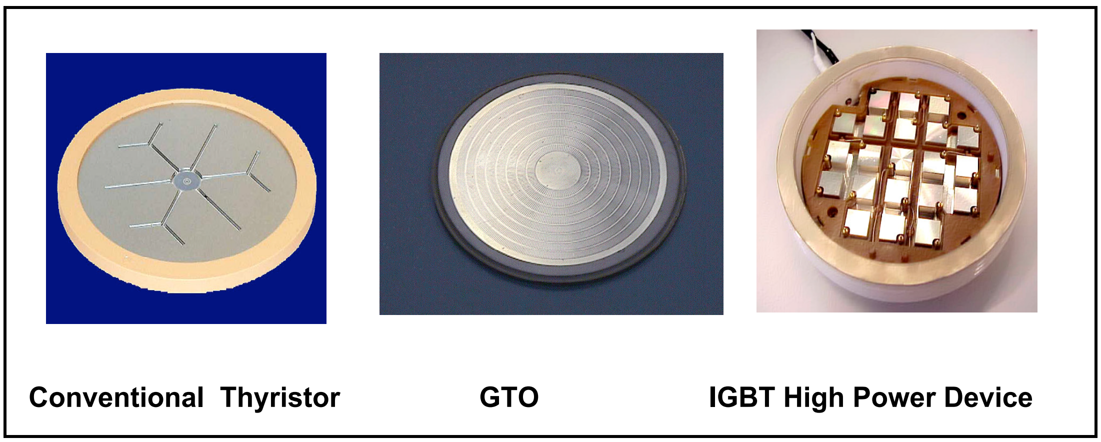

Figure 7.4-4. Power Semiconductor Device Components

Note for Figure 7.4-4: *The conventional thyristor is made on large single wafers. The GTO thyristor is also made on large single wafers but with a large number of cathode islands to enable turn-off. The IGBT high-power device is several small IGBTs housed in a large package. The conventional thyristor and the IGBT photographs are courtesy of Siemens, and the GTO thyristor photograph is courtesy of Silicon Power Corporation.*

Apart from the cost of the different devices, the device ratings and characteristics and device packaging in a power electronics building block have a high leverage on the cost, weight, and losses of power electronics equipment. The high leverage of these devices and their packaging into a PEBB includes the cost of all that surrounds the devices, including snubber circuits, gate drives, on-board power supply for the gate drives, magnetics, capacitors, filters, cooling equipment, and so forth. Therefore, the design of high-power electronics equipment would usually be based on the devices with best available characteristics, even at higher prices.

With large and long current-pulse requirements for turn-on and turn-off of current-driven gates, not only are these losses important in relation to the total losses, but the cost of the driver circuit and power supply can equal the device cost itself. The size of all components that accompany a power device increase the stray inductance and capacitance, which, in turn, affect the stresses on the devices, switching times, and snubber losses. Given the importance of coordinating the device and the gate driver design and packaging, the future trend will be to purchase the device and the driver as a single package.

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MCTL DATA SHEET 7.4-7. MOS-CONTROLLED THYRISTOR (MCT) TECHNOLOGY

Critical Technology Parameter(s)	I_{peak} ≥ 40 kA V_{peak} ≥ 2 kV Action ≥ 0.25 MA^2/sec Charge ≥ 15 C
Critical Materials	High-purity, low-defect silicon or silicon carbide, particularly for large-area wafers for high-current devices.
Unique Test, Production, Inspection Equipment	Semiconductor material processing equipment.
Unique Software	None identified.
Major Commercial Applications	Medium power conditioning and control in commercial hybrid vehicles; high-frequency/ high energy-density applications.
Affordability Issues	Cost tends to increase with device speed and power handling capability.
Export Control References	WA ML 11;[34] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

The MCT has exhibited the capability to operate at a current density at least three times that of an SCR. The critical parameters are based on a current density capability of 10 kA/cm^2. The major advantage of the MCT is its low voltage drop and the resulting high switching efficiency. The state-of-the-art values listed for the SCR, MCT and GTO are those measured on representative devices at the Army Research Laboratory (ARL) Electronics and Power Sources Directorate (EPSD). Nonirradiated devices have a lower voltage drop, at the expense of increased carrier lifetime and increased recovery time.

In Japan, MCTs are also referred to as MOS-Assisted Gate Thyristors (MAGTs).

[34] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.4-8. SILICON-CONTROLLED RECTIFIER (SCR) TECHNOLOGY

Critical Technology Parameter(s)	I_{peak} ≥ 150 A V_{load} ≥ 4 kV Action ≥ 15 MA^2/sec Charge ≥ 125 C
Critical Materials	High-purity, low-defect silicon or silicon carbide, particularly for large-area wafers for high-current devices.
Unique Test, Production, Inspection Equipment	Semiconductor material processing equipment.
Unique Software	None identified.
Major Commercial Applications	Power conditioning and control in high-power/high-current applications, such as EV drive (particularly ground and marine systems) and industrial power applications.
Affordability Issues	Cost tends to increase with device speed and power-handling capability.
Export Control References	WA ML 11;[35] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

The SCR is the basic solid-state closing switch. The SCR's major advantages are that it can conduct more current per unit area than any other solid-state switch and that its simple structure and ease of fabrication make it the most cost effective.

The advent of large-diameter silicon processing facilities will make possible the fabrication a single switch capable of a peak current of 400 kA and blocking voltage of 10 kV in both directions. New packaging techniques, such as the all-silicon package, significantly reduce overall package size and the thermal management problem.

[35] Including associated software and technology specified in WA ML 18, 21, and 22.

MCTL DATA SHEET 7.4-9. WIDE BANDGAP (WB) SEMICONDUCTORS

Critical Technology Parameter(s)	SiC diode current > 40 A SiC single chip switch current > 25 A for any voltage SiC switch or diode module current > 100 A SiC switch voltage at > 10 A > 600 V SiC switch or diode voltage > 3,000 V for any current
Critical Materials	WB semiconductor materials include SiC, III-Nitrides, diamond, and titanium carbide (TiC) and thermally stable dielectric materials with low dielectric constants and large field strengths; low resistance; high thermal stability packaging; direct bonded cooper (DBC), aluminum indium nitride (AIN)-based materials; low resistivity (< 10^{-6} Ω-cm^2); thermally stable (> 600 °C) ohmic; and Schottky contact technology. SiC substrates: low micropipe defect density: < .5/cm^2 for 3-in. diameter substrates (in production), (0.22/cm^2 defect density has been demonstrated in the lab), SiC Schottky diodes.
Unique Test, Production, Inspection Equipment	Surface-mount technology; electro-deposition processes; large volume expitaxial reactors; large-volume substrate production facilities for WB semiconductor materials such as SiC, III-Nitrides, BC, diamond, TiC; and thermally stable dielectric materials with low dielectric constants and large field strengths. Material issues: micropipe and other defect effects; large area growth. Fabrication issues: dry etching, ion implantation, oxidation, ohmic contacts. Device design issues: transistors, thyristors, dynistors, IGBTs, MOSFETs, and MCT design. Growth of materials with near-zero defects.
Unique Software	None identified.
Major Commercial Applications	High-power utility electric power distribution; high-frequency transceiver for personal communication; opto-electronic applications for visible emitters [blue and green light emitting diodes (LEDs) and laser diodes] with significantly reduced power consumption.
Affordability Issues	None identified.
Export Control References	WA ML 11;[36] WA Cat 3; USML XI; CCL Cat 3.

BACKGROUND

Several potential WB materials are applicable to power semiconductors; however, very little WB material research is taking place. For power semiconductor devices, the most investment, by far, has been in SiC materials. The next most investment has been in Gallium nitride materials.

WB semiconductors are an enabling technology for many military systems (e.g., space-based observation and weapons platforms; ground-based systems, such as DE, radar, and laser systems). Further, these systems require electronics that can tolerate high-temperature operations, thereby eliminating bulky and heavy cooling systems. WB semiconductors can also be used for power conditioning and PFN applications for all the aforementioned systems and platforms, which are designed to be employed over the next 20 years (10- to greater than 100-kV-type levels; discrete high current devices greater than 1,000 A; high-operating junction temperatures greater than 500 °C; reliable device

[36] Including associated software and technology specified in WA ML 18, 21, and 22.

operating temps greater than 450 °C; discrete device blocking voltages greater than 5,000 V; and power switching frequencies greater than 200 kHz for power levels above 10 kW and greater than 500 kHz for power levels from 1 to 10 kW).

Silicon Carbide (SiC)

In principle, SiC material can be used to make any of those devices discussed in the Power Semiconductors Data Sheet (see Data Sheet 7.4-6). SiC offers the advantages of much lower switching losses, high-voltage capability (20 kV rating per device), and high-temperature capability. However, the material is expensive, and a large number of small chips have to be connected in parallel for power applications. Even though SiC devices are expensive, they have a very high leverage on converter size, losses, weight, and cooling requirements and the potential for high PWM frequencies. Because of the high value of weight, losses, and size, use of SiC devices in marine applications may seem inevitable. SiC will enable increased integration of power electronic components. The high power density of SiC will allow a greater portion of the power converter to be integrated into modules, thus enabling automated manufacture. The higher voltage capability of SiC will enable PWM conversion in the greater than 10-kV class distribution systems without transformers—further reducing size, weight, and cost.

SiC Schottky Diodes

SiC Schottky diodes are an extremely important component for power converters. Of particular importance is the use of SiC diodes in a PWM voltage sourced converter with Si-based main devices. Replacing an Si PIN diode with an SiC Schottky diode in a converter (retaining the Si switches) will reduce the converter power dissipation by approximately a factor of two. This much-reduced reverse recovery current can double the power density and allow operation up to 10 kHz, eliminating the need for filters. Commercial 600 V and 1,200 V Schottky diodes with current rating up to 10 A are available. The 50-A, 600-V to 1200-V SiC Schottky diode parts will be available in the future. SiC Schottky diode 600-V modules, with parallel chips, up to 150 A have been demonstrated. Modules with Si switching chips and SiC diodes are becoming available.

SiC Switches

The first SiC commercial switches were expected to be available sometime in 2004. The voltage range of these switches will likely be in the 1200 V to 1500 V @ 5 to 10 A. The 1200 to 1500-V power switching devices are appropriate for 450-V AC and 600-V DC to 650-V DC equipment allocations. To achieve higher current levels, multiple die will have to be paralleled within a module. For example, for 50-kW, 450-V AC motor controller, it appears that an approximately 150-A module will be required, and, for a 50-kW DC/DC converter, an approximately 75-A module will be required.